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FEASIBILITY ASSESSMENT OF CONCEPTUAL 105-mm M68 COMPOSITE TUBES

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ABSTRACT

A study is reported in which the thermal, stress, fabrication, durability, and weapon interface problems associated with implementation of composite materials in a 105-mm M68 tube configuration are evaluated. It is shown that thermal factors associated with the lowered heat capacity and thermal conductivity of composite materials compared to that of steel are best minimized by judicious placement of composite material along the tube. The dominant thermal effect associated with replacement of steel by composite material is determined to result from the composite's low heat capacity per unit volume (roughly 60% that of steel). Increase of composite thermal conductivity would do little toward reduction of required composite working temperature in desired high rate firing schedules.

A composite tube design which achieves at least a 10% reduction in M68 tube weight is suggested. Based on use of polyimide-graphite composite material, the design is shown to withstand a 65-round continuous burst of M456 ammunition at 8 rounds/min.

The composite tube designs were evaluated for temperature and stress profiles through application of a finite element computer code developed specifically in this work. The code accounts for pressure, thermal, cure, and autofrettage stresses prior to, during, and after firing. The computer listing is given in the report.

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LIST OF SYMBOLS

A	=	Area
C	=	Heat capacity
D	=	Diameter
E	=	Emissivity
E_s	=	Elastic modulus for steel
E_c	=	Elastic modulus for composite
h_c	=	Convection coefficient
K	=	Thermal conductivity
K_{EFF}	=	Effective thermal conductivity
L	=	Length
M	=	Mass
P_c	=	Chamber pressure
Q_o	=	Initial heat input $\frac{Btu}{Ft^2\text{-}rd}$
q_{con}	=	Convective heat flux
q_{rad}	=	Radiative heat flux
S	=	Shear area
T_o	=	Outer barrel temperature
T_{eff}	=	Effective gas temperature
T_e	=	Ambient temperature
ΔT	=	Temperature rise
ΔT_{sc}	=	Average temperature rise in steel core
ΔT_{cure}	=	Cure temperature rise above ambient
U_{eff}	=	Effective conductance
V	=	Air velocity
X	=	Volume fraction
α	=	Expansion coefficient
ρ	=	Density
μ	=	Poisson's ratio
σ	=	Tensile strength

LIST OF SYMBOLS (cont.)

$(\ )_m$	Refers to metal or muzzle
$(\ )_s$	Refers to steel
$(\ )_c$	Refers to composite
$(\ )_b$	Refers to bore
$(\ )_B$	Refers to breech
$(\ )_T$	Refers to tape
$(\ )_x$	Refers to axial direction
$(\ )_y$	Refers to hoop direction

INTRODUCTION

The recent need for very high mobility guns with high precision makes the idea of a very light, but stiff composite tube very appealing. Such a tube would permit much reduced gun weight while maintaining a great deal of precision. Small reductions in tube weight would result in significant weight savings in support components for the barrel and, therefore, would result in a substantial reduction in overall system weight. Composite gun tubes have been shown feasible in limited testing; for example, the work of Douglas[1] demonstrated performance gains in precision with reduction in tube weight. The chief problems associated with utilization of composite tubes result from tube heating during firing. The tube heating produces a significant temperature increase of the gun barrel with each shot. Even at low rates of fire, there is continual temperature increase of barrel components such that tubes can attain very high temperature levels when substantial numbers of rounds are fired. M68 cannon tubes are presently being considered for use against armor and with possible automatic loading. In this instance, even less cooling of the tube is available between shots. Therefore, the attendant tube temperature rise in a given number of rounds would naturally increase.

With the addition of a fibrous-resin composite structure exterior to the metallic tube, the temperature problem is further worsened. In general, such fibrous composites have low heat capacity per unit volume and thermal conductivity; hence, the substrate metallic tube can attain very high temperatures in very few rounds. Furthermore, cooling of this metallic tube is essentially eliminated through the addition of the outer composite structure; thus, little decrease in tube temperature will obtain between round complements. Because of the weight reductions possible through the application of a composite barrel, there is justification for study and analysis of methods by which this tube configuration can be implemented. This is the objective of the proposed work.

Calspan's approach to the problem has been to establish potential tube temperatures associated with rapid repetitive fire of ammunition for chosen candidate composite M68 cannon tube designs which result in significant tube weight reduction. Following this, Calspan selected from available composite materials that which appeared to possess the highest potential for application to this problem. In this selection account was taken of tube installation and operational factors as well as stress factors as a result of thermo-mechanical effects. These factors were determined through application of a working finite element computer code developed specifically for this effort. The code accounts for heat/temperature effects due to firing, and thermal, pressure, and auto-frettage stress histories during tube operation.

Temperature/stress composite profiles for a proposed composite M68 tube design for which tube weight is reduced by more than ten percent are computed to be within acceptable limits. The thermal performance of the suggested composite material is confirmed through a very brief demonstration test.

DISCUSSION

Factors Affecting Tube Heating and Temperatures

In the firing of any cannon system, the barrel is subjected to pulses of heat which correspond to the individual shots fired. The heat pulses are a consequence of the high-velocity, high-pressure, high-temperature gases flowing along the surfaces of the bore and thus transferring heat from the propellant gases to the bore surface. Each individual heat pulse produces a corresponding bore-surface temperature excursion which increases the bore temperature to a peak level during the firing period. Following this heating period, cooling to the interior of the barrel wall reduces the bore-surface temperature to a level substantially below the peak. The bore-surface temperature diminishes to a level essentially equal to that of the average barrel temperature, unless the bore is subjected to another firing pulse. If so, the bore-surface temperature during the second firing increases again to a new peak value. Thus, the bore-surface temperature oscillates between the peak value and some residual value at the instant of the next firing pulse. In the meantime, energy from each shot is stored within the barrel proper, thus increasing the average barrel temperature by some incremental amount per shot.

Figure 1 illustrates for a 75 mm gun the computed values of peak, residual, and average temperatures as a function of shots fired. The effects of these temperatures on barrel performance are severalfold: First, the peak bore temperatures are instrumental in reducing the capacity of the surface to withstand the gas flow and shear stresses induced during the ballistics cycle. Sufficient reduction in capacity would permit gas erosion. Second, as the residual temperatures increase, the barrel's interior surfaces weaken; thus, mechanical forces from the rotating band and projectile body can produce mechanical damage to the bore or rifling. Third, with continuous firing, the average temperature of the barrel will achieve temperatures beyond the barrel's capacity to withstand the internal pressure stresses or dynamic forces of firing; thus, barrel deformation can result. Failure modes which can be associated with gun firings differ, depending upon the performance and caliber of the weapon under consideration.

In the conventional small-arms gun systems, barrel failure is normally associated with increase in the average barrel temperature and is the result, for the most part, of mechanical damage caused by projectile forces on the weakened barrel surface. For these small-caliber barrels, many rounds need to be fired to achieve sufficiently high barrel temperatures before erosion or wear can take place. Since the heat input per shot is small--much lower than that of the large-caliber cannons of interest in this program--the low inputs result in relatively small values of thermal gradients and residual temperatures.

The large-caliber gun systems of interest in this study have their peak temperature and wear associated with extremely high peak barrel temperatures, and the dominant mechanism for loss, in general, is gas erosion. In these

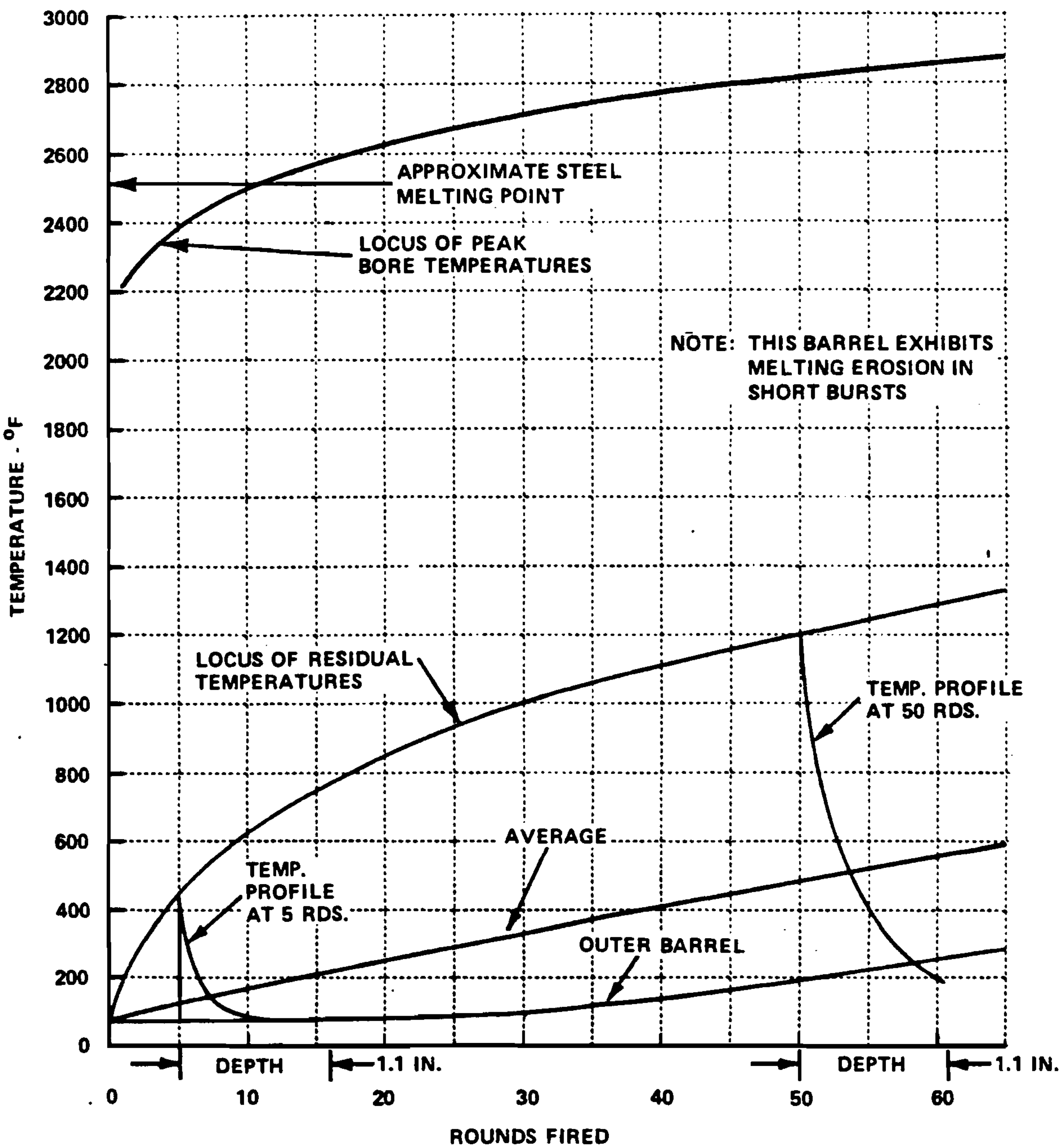

Figure 1. Computed Peak, Residual and Average Temperatures as a Function of Shots Fired in a 75 mm High Velocity Gun

systems, bore-surface melting can actually be obtained on any given shot. Thus substantial erosion can be associated with very limited firings. In particular, the average barrel temperature of large-caliber guns has direct bearing upon the peak bore temperatures reached in any particular shot. Calspan has established, through many analytical computations, that the increase in peak barrel temperature is roughly 1/3 to 1/2 of the corresponding increase in average barrel temperature; for example, if the peak barrel temperature in a single shot for a large-caliber gun is $2000^{\circ}F$, this peak barrel temperature will increase to $2200^{\circ}F$ when the average barrel temperature has been increased by $400^{\circ}F$. Since barrel wear/erosion is a strong function of peak barrel temperature, advanced composite barrels must ultimately be assessed with respect to erosion performance. This is beyond the scope of the present effort.

With respect to composite gun tubes, temperatures within the metallic substrate are increased for three reasons: First, because the metallic portion of the tube must be diminished in thickness to provide measurable reduction in tube weight, less metallic material is available for heat storage; hence, temperature rise per shot of the metallic substrate is increased. Second, because the heat capacity per unit volume of the external composite structure is much below that of the metal, the amount of heat which can be absorbed by the composite per unit temperature increase is less than the same volume of metal. Third, at very substantial rates of fire (eight rounds per minute for 63 rounds), it is likely that the lower thermal conductivity of the composite will limit heat transfer such that exterior cooling which normally provides only minimal relief for barrel temperatures will be even less effective. There is, therefore, a possibility that gas erosion of the bore would reach measurable values in such burst lengths, thus minimizing the useful life of the tube. Additionally, under continuous firing conditions, where the substrate would achieve temperatures in excess of $750^{\circ}F$ for significant depths, it is possible that much of the residual stress associated with the autofrettaging of the tube may be lost. As a result, the fatigue life of the barrel material could be diminished to an extent that the gun barrel may become logistically not cost-effective. For any design utilizing the composite tube technique, care must be exercised to account for the thermal factors indicated above while at the same time maximizing the barrel weight reductions with minimal impact on tube life and cost.

The composite material itself must possess mechanical properties permitting its utilization at relatively high interfacial temperatures of contact with the metallic tube substrate. This would permit the most effective logistical and operational application of the gun system. It is also desirable that the thermal conductivity and heat capacity of the composite material be sufficiently high that energy initially stored in the metallic substrate can be transferred to the body of the composite material, thereby minimizing the temperature response of the substrate. This will have a threefold effect: 1) it will lower the temperature of the substrate; 2) it will lower the interfacial temperature requirements for the composite; and 3) it will permit greater external heat loss through development of increased external temperatures. Thus, it is important that the effect of composite material addition to the tube be assessed with respect to its affect on the temperatures of most concern in barrel design, namely, the surface and average temperature of the metallic substrate and the metal/composite interfacial temperature.

Tube Heat Input Factors

The basic factors which determine the temperature response of a composite gun tube are the bore heat input per shot as a function of residual bore temperature and the internal thermal characteristics of the tube. Bore heat input values are best obtained where possible from measurements taken during actual firing tests. For the M68 gun tube of interest here, Calspan has previously established heat input factors for specific stations along its length as illustrated in Figure 2. Here, we observe that the initial heat input Q_o at any station diminishes linearly with increased bore temperature reaching a zero level at a temperature T_{eff} which depends upon axial tube location. For the M68 tube Figure 3 illustrates values of Q_o and T_{eff} along the tube taken from the work of Reference 2. These heat input values have been utilized in subsequent thermal analysis of this work.

Heat Loss Factors

Heat losses from a gun tube are, for the most part, dependent upon the degree of convective air flow over its outer surface and net radiation loss to the surroundings. Convective heat transfer losses for large tubes in "free" or mild forced convective environments are usually very small compared to heat gains from the propellant gases. The convective loss is determined by the outer tube temperature, the environmental temperature, and the convection coefficient through the relation.

$$q_{con} = h_c \, (T_o - T_e) \tag{1}$$

The convection coefficient in air, h_c, is approximated by

$$h_c = \underbrace{0.58\left(\frac{V}{D^{0.618}}\right)^{0.618}}_{\text{Forced Convection}} + \underbrace{0.24 \sqrt[4]{\frac{\Delta T}{D}}}_{\text{Free Convection}} \tag{2}$$

based on Hilpert's constants[3]. In this

V is the air velocity - ft/sec.
D is the diameter - ft.
ΔT is the temperature difference, $(T_o - T_e)$

As an illustration of magnitudes, consider an ambient wind velocity of 10 mi/hr over the surface of a 400°F tube. For a tube outer diameter of 8 inches, the convection coefficient is about 4.7 BTU/ft^2 - hr - °F the convective loss would then be 4.7 (400-70) = 1550 $\frac{BTU}{HR - ft^2}$ of outer tube surface. This is to be compared to a heat gain of nominally 75 x 8 x 60 = 36000 BTU/hr-ft^2 of inner bore surface imposed by a firing rate of 8 rounds/min. Thus the convective losses are clearly small relative to gains throughout the firing period.

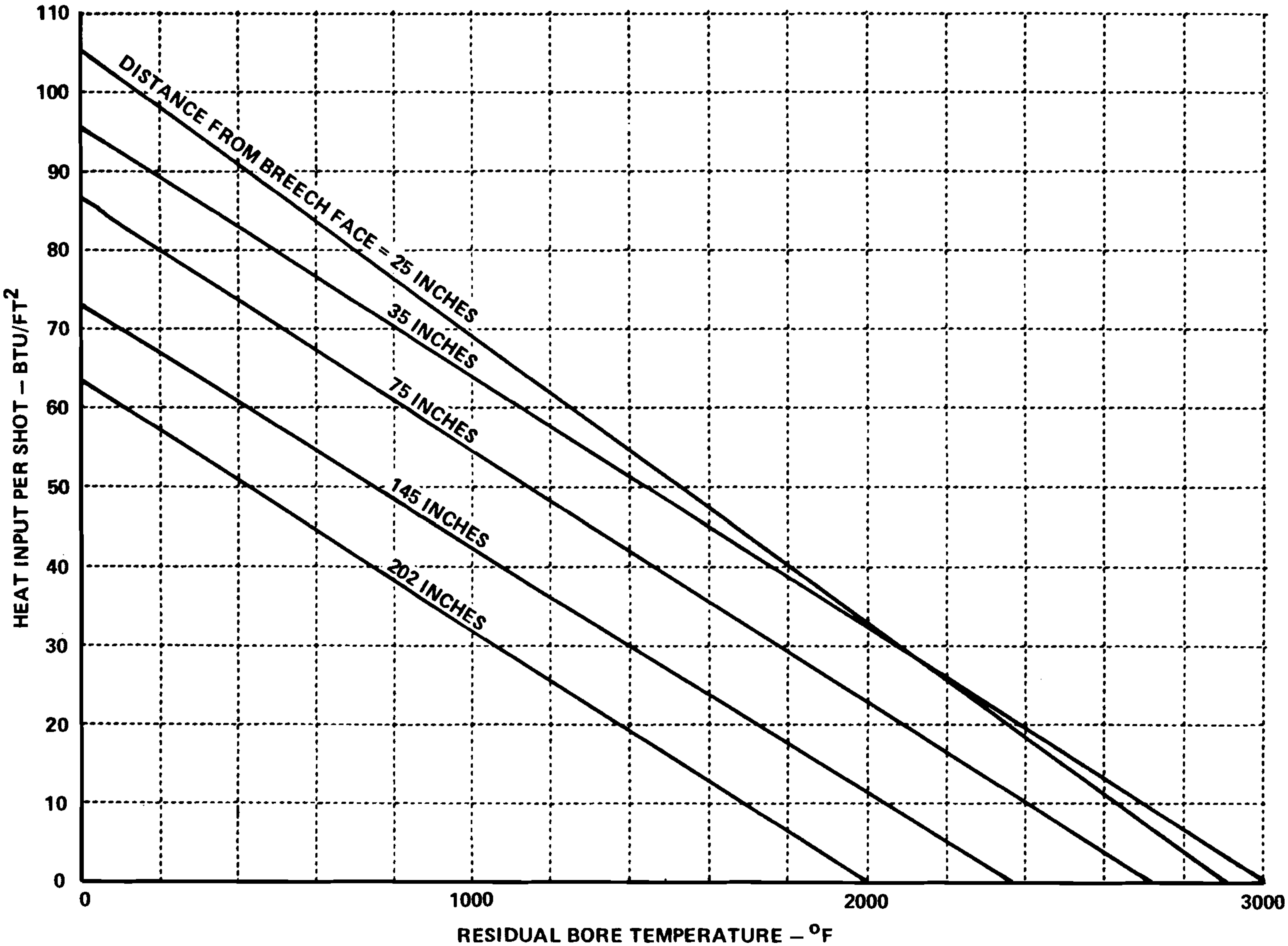

Figure 2. Bore Heat Input as a Function of Residual Bore Temperature Along the M68 Tube

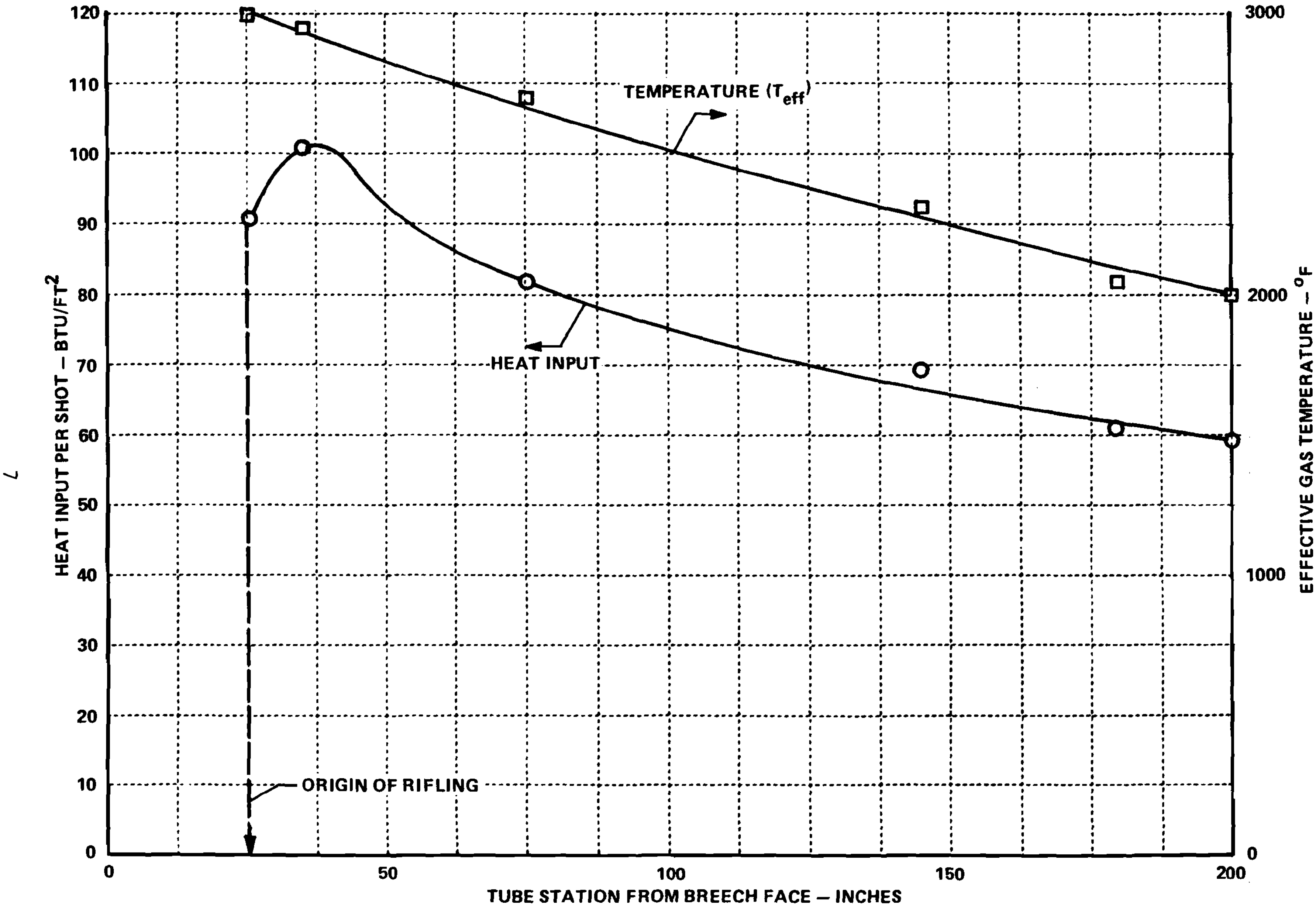

Figure 3. Heat Input and Effective Gas Temperature Along M68 Tube

The radiation contribution to loss is of the same order as that of convection and is given by

$$q_{rad} = 0.174 \quad E \left[\left(\frac{T_o + 460}{100} \right)^4 - \left(\frac{T_e + 460}{100} \right)^4 \right] \tag{3}$$

in which E is the emissivity of the tube surface usually taken as unity. The radiation loss for a 400°F tube becomes approximately $q_{rad} = 815$ BTU/hr-ft^2 of outer tube surface, again small compared to nominal heat gains.

The total loss from any station of the tube is thus given by

$$q_{loss} = q_{con} + q_{rad} \tag{4}$$

and may be determined by use of equations 2 and 3 above.

Heat Conduction and Internal Temperatures

Conduction of heat to the interior of the composite cylinder at any axial station was determined by application of Dusinberre's[4] method for numerical computation of transient heat flow. In this method, the general partial-differential equations are replaced by finite-difference substitutions based upon a balancing of heat flow within each of a number of elemental subvolumes, into which the cylindrical section has been divided. Figure 4 illustrates a general subdivision of a particular composite tube section as used in this work. As is shown, the section is considered to consist of two concentric regions separated by a thermal resistance representing interface contact. The thermal masses of each subvolume are considered generally to be concentrated at their central point, and heat is imagined to be conducted between points through a network of fictitious heat conducting rods of appropriate thermal conductance. Using the method, temperatures within each element as a function of time are determined using heat balances from which new temperatures for each element after a specific time interval are calculated based upon its and neighboring element temperatures. In this manner, the spacial distribution of temperature is built with time for any given property values and boundary conditions. Stability of the solution is assured by selecting the computational time interval such that the second law of thermodynamics is not violated. The required time interval is computed within the code and is dependent upon the input parameters.

In keeping with the desire for simple feasibility assessments and to minimize complexity in the model, all properties are considered constant and must be specified for each calculation . Furthermore, axial conduction is considered negligible compared to radial conduction. Temperature and stress computations are direct and in this sense the scheme is considered explicit. A complete listing of the computer code is given in the appendix along with a representative computation.

M68 Tube Temperatures

Through application of the above heating factors and the conduction code, temperatures at significant locations in the M68 tube when firing M456 ammunition at a rate of 8 rounds/min were computed. Figure 5 illustrates resulting average barrel temperatures at these stations at 63 rounds. The relative thermal gradient through tube wall is also suggested through the computed inner to outer wall temperature differences given in the figure. As an example of temperature response, the inner, outer, and average tube temperature for the positions at 35 and 202 inches are as shown in Figure 6. These represent stations having the greatest and the least thermal gradient

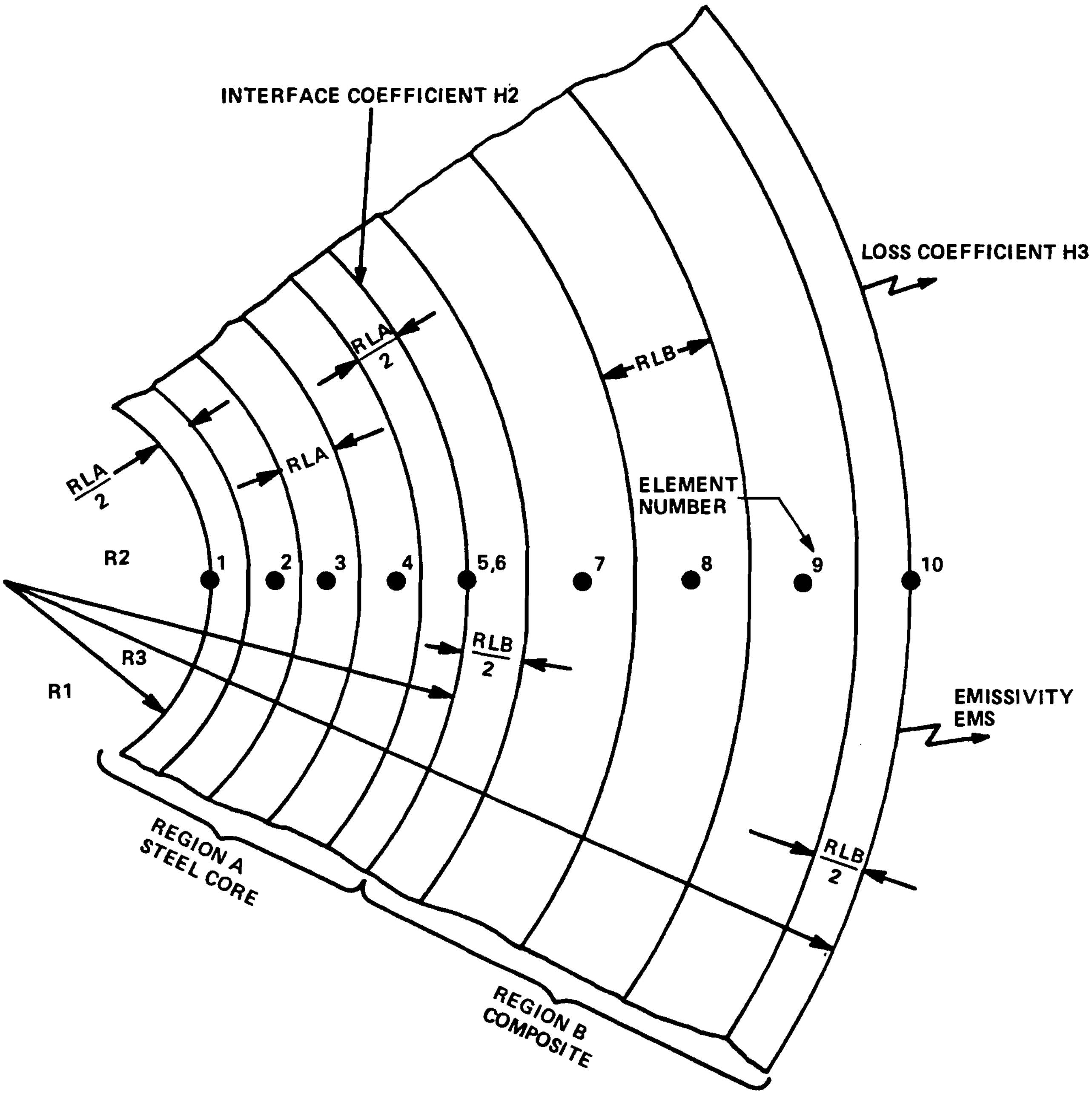

Figure 4. General Subdivision of Axial Sections into Radial Elements

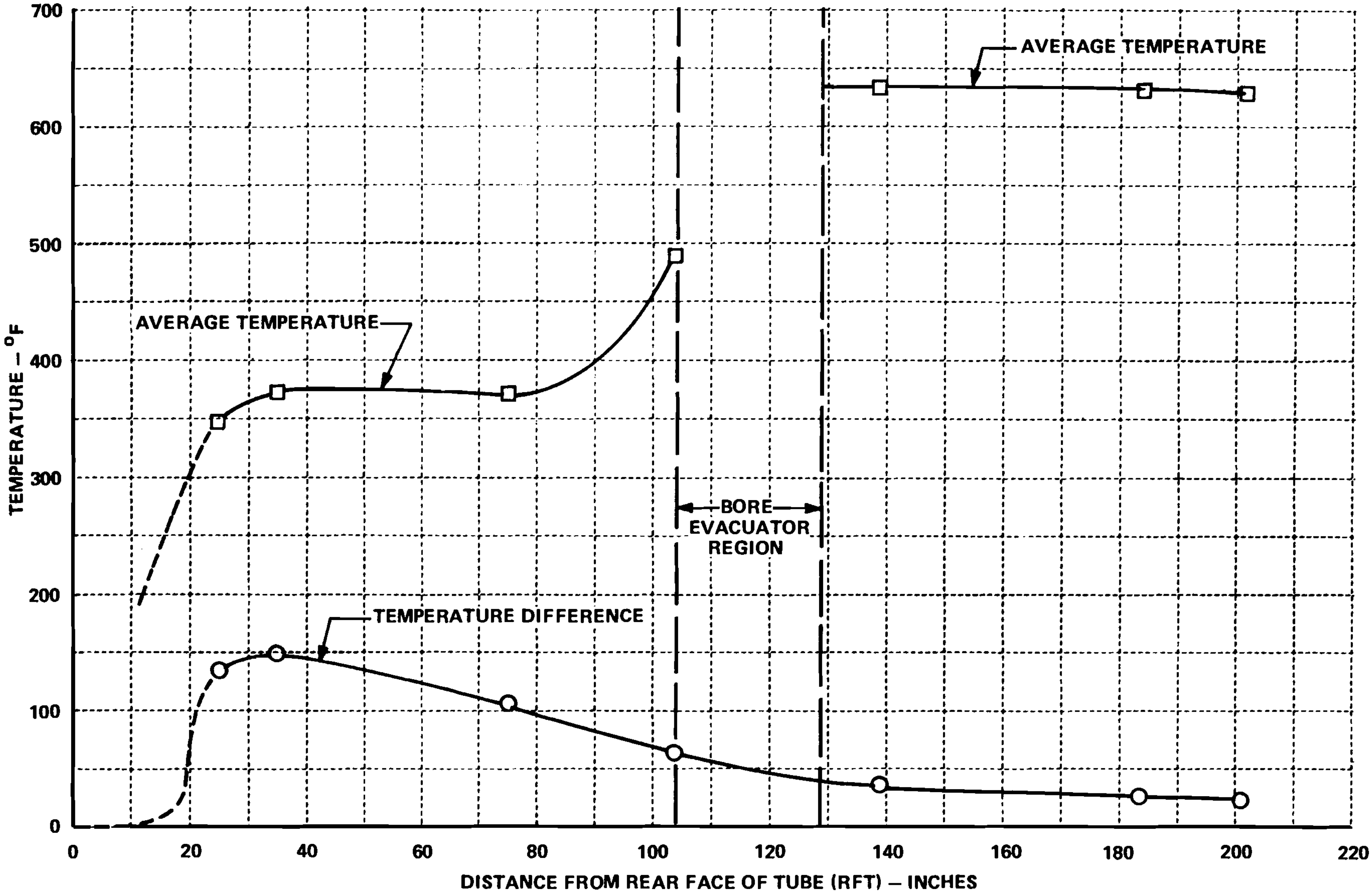

Figure 5. Computed Barrel Temperatures for the M68 Tube at 63 Rounds Fired at 8 Shots/Min

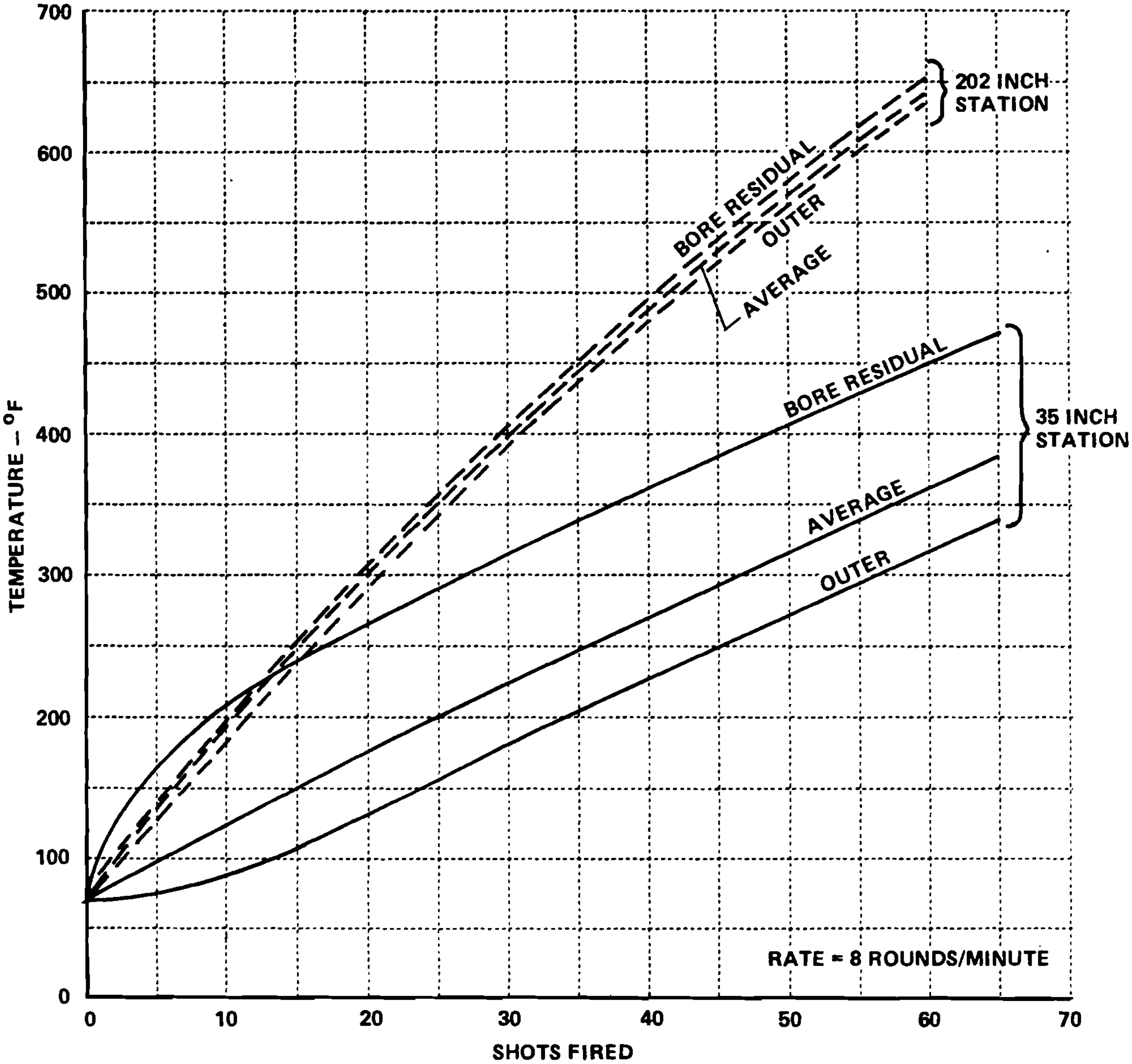

Figure 6. Relative Thermal Gradients (Monolithic Tube)

respectively. The effect of firing rate on the limiting temperature for the 202 inch station is given in Figure 7.

The computations indicate essentially two levels of temperature along the barrel. From the breech to the location of the bore evacuator, the temperature reaches a level of about 375°F. Beyond the evacuator, the barrel average temperature reaches nearly 640°F. Major thermal gradients, while less than 150°F, are confined to regions near the origin of rifling. Although limiting temperatures may be reduced somewhat by a lowering of firing rate, only modest reductions are indicated within meaningful firing conditions.

Composite Tube Design Considerations

Weight/volume

The volume or outer dimensions of the tube are constrained by practical considerations. First, the tube must interface with the tank mount M140A1. This limits the basic outer diameter of the tube to that of the current tube, or 8.9 inches. Second, provision must be made to accommodate the existing bore evacuator. Because this must be positioned from the muzzle end, the outer diameter of the tube forward of the evacuator can be no bigger than the inner diameter of the evacuator or 6.08 inches. Obviously the tube must have the existing tube dimensions beneath the evacuator. Hence, for the majority of tube length little increase in tube outer diameter is allowable.

The weight of any particular section of a composite tube is given by the relation

$$W/L = \frac{\pi}{4}\left[\rho_s\left(D_i^2 - D_b^2\right) + \rho_c\left(D_c^2 - D_i^2\right)\right] \tag{5}$$

The weight change relative to the monolithic steel tube is

$$\Delta W/L = W/L - \frac{\pi}{4}\rho_s\left(D_o^2 - D_b^2\right) \tag{6}$$

$$\Delta W/L = \frac{\pi}{4}\left[\left(\rho_s - \rho_c\right)D_i^2 - \rho_s D_o^2 + \rho_c D_c^2\right] \tag{7}$$

Here,

D_b is the bore diameter

D_i is the diameter to the composite steel interface;

D_o is the original monolithic tube outer diameter;

D_c is the composite tube outer diameter;

$\rho_s - \rho_c$ is the density difference between steel and composite.

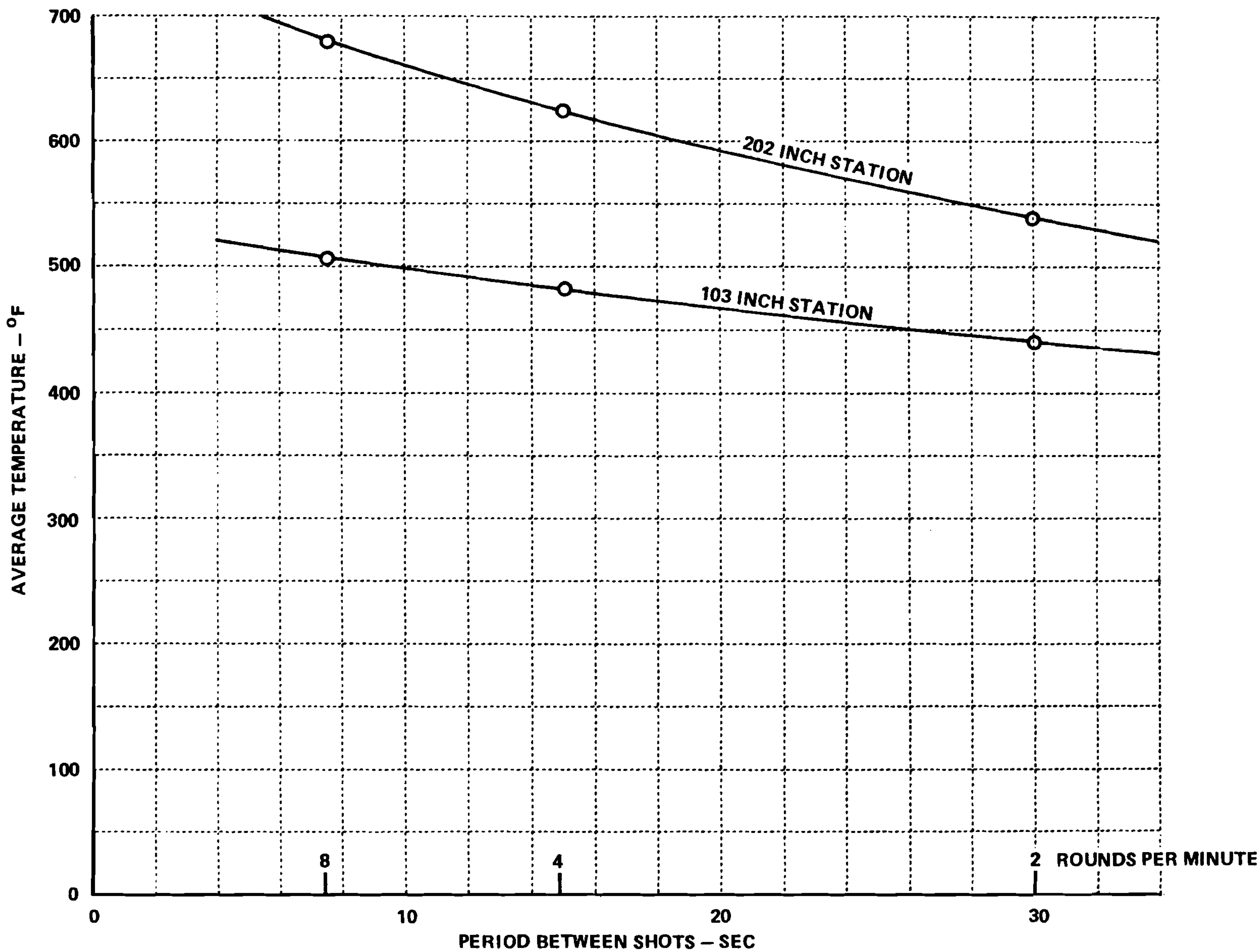

Figure 7. Effect of Firing Rate on Average Tube Temperatures

Since it is likely that the composite tube diameter would be at least that of the original tube ($D_o = D_c$), equation (7) simplifies to

$$\frac{\Delta W}{L} = \frac{\Pi}{4} \left[(\rho_s - \rho_c) \; (D_i^2 - D_c^2) \right] \tag{8}$$

The equation 8 indicates that the magnitudes of weight reduction afforded by the application of composite material depends greatly upon the available diameter of the tube. Obviously, the smaller the diameter, the less reduction in weight possible at any tube section.

For example,near the muzzle of the M68 cannon, the tube outer diameter is about 5.9 inches. Then the approximate weight reduction available through incorporation of composite having ρ_c = 110 lb/ft^2 is given in Table 1 for various diametrical interface D_i values.

TABLE 1

Weight Reductions (muzzle end)

Interfacial diameter - inches	Weight Reduction per unit length - lb/ft
5.75	3.62
5.5	9.45
5.25	15.0
5.00	20.3
4.75	25.3
4.50	30.1

We desire at least a 10% weight reduction compared to that of the existing M68 tube. This amounts to about 165 lb. The approximate distances near the muzzle over which the reductions of Table 1 can take place is about 75 inches. Thus, a weight reduction of 26.4 lb/ft is needed. To achieve this with composite material addition at the muzzle section, the steel/composite interface diameter would then need to be 4.75 inches leaving very little steel in this section (less than 0.325 wall).

The situation is improved considerably when we consider obtaining weight reductions by modifications near the tube breech. Here the diameter is about 8.9 inches and the possible weight reductions per unit length are given in Table 2.

TABLE 2

Weight Reductions (breech end)

Interfacial diameter-inches	Weight reduction per unit length lb/ft.
8.5	14.4
8.25	23.1
8.00	31.5
7.75	39.6
7.50	47.5
7.25	55.2
7.00	62.6

In this region of the tube at least 50 inches of tube may be altered and the 165 lb. weight reduction may be obtained with an interfacial diameter of 7.75 inches, or using composite 0.58 inch thick. Thus significant steel remains to absorb thermal energy from firing.

Heat Capacity

Replacement of steel with composite in any amount will tend toward increase in working tube temperature as a consequence of the reduced heat capacity per unit volume for the composite material in addition to its reduced thermal conductivity. The heat absorbed per unit length by the composite tube is given by:

$$Q_c = \frac{\Pi}{4}\left[(C\rho)_s\left(D_i^{\,2} - D_b^{\,2}\right)\Delta T_{sc} + (C\rho)_c\left(D_c^{\,2} - D_i^{\,2}\right)\Delta T_c\right] \qquad (9)$$

This is compared to a monolithic steel tube of the same diameter given by:

$$Q_s = \frac{\Pi}{4}\left[(C\rho)_s\left(D_c^{\,2} - D_b^{\,2}\right)\Delta T_s\right] \qquad (10)$$

Under the assumption that nearly the same heat must be absorbed by each in the same number of rounds fired, * we get

$$\left(D_i^{\,2} - D_b^{\,2}\right)\Delta T_{sc} + \frac{(C\rho)_c}{(C\rho)_s}\left(D_c^{\,2} - D_i^{\,2}\right)\Delta T_c = \left(D_c^{\,2} - D_b^{\,2}\right)\Delta T_s \qquad (11)$$

*This is valid where $\Delta T_s \ll$ Teff

Two limiting situations may be considered. First, assume the composite to be highly conductive so that $\Delta T_{sc} = \Delta T_C$. Here,

$$\Delta T_{sc} = \frac{\left(D_c^{\,2} - D_b^{\,2}\right) \Delta T_s}{\left(D_i^{\,2} - D_b^{\,2}\right) + \frac{(C\rho)_c}{(C\rho)_s} \left(D_c^{\,2} - D_i^{\,2}\right)} \tag{12}$$

Second, assume that the composite conducts little heat so that $\Delta T_c \longrightarrow 0$. Here,

$$\Delta T_{sc} = \frac{\left(D_c^{\,2} - D_b^{\,2}\right) \Delta T_s}{\left(D_i^{\,2} - D_b^{\,2}\right)} \tag{13}$$

Typical values for heat capacities per unit volume $(C\rho)_c$ and $(C\rho)_s$ are 30 and 58 BTU/FT^3 -^{o}F respectively. Recalling that D_i would need to be 4.75 inches near the muzzle end to attain desired weight reduction with D_c = 5.9 and D_b = 4.1 we get:

$\Delta T_{sc}\big)_m = 1.49\ \Delta T_s\big)_m$ From (12)

$\Delta T_{sc}\big)_m = 3.13\ \Delta T_s\big)_m$ From (13)

For the breech section D_i = 7.75 D_c = 8.9 D_b = 4.1 we get:

$\Delta T_{sc}\big)_B = 1.18\ \Delta T_s\big)_B$ From (12)

$\Delta T_{sc}\big)_B = 1.44\ \Delta T_s\big)_B$ From (13)

Based upon Figure 4, resulting temperatures at 63 rounds for the composite in the above limiting situations are:

For the muzzle,

$T_{sc}\big)_m = 1.49\ (635-70) + 70 = 874\ ^oF$ (minimum)

or $T_{sc}\big)_m = 3.13\ (635-70) + 70 = 1840\ ^oF$ (maximum)

For the breech,

$$T_{sc}\Big)_B = 1.18\ (375-70) + 70 = 430\ ^{o}F\ \text{(minimum)}$$

or $$T_{sc}\Big)_B = 1.44\ (375-70) + 70 = 509\ ^{o}F\ \text{(maximum)}.$$

The essential point of these results is that attainment of weight reduction through application of composite material to the tube structure results in significant increase in tube working temperature simply as a consequence of reduced heat storage capacity of the composite material. Furthermore, estimated temperatures suggest little hope of attaining desired weight reduction goals through muzzle section modifications using currently available composite materials and/or adhesives. Computations do, however, offer hope of attaining weight goals by modifications applied to the breech section of the M68 tube where only modest temperature increases and levels are indicated. In this region the tube wall is thick and therefore significant weight reduction can be achieved with demonstrated minimal extension of operational working temperature level or sacrifice in firing schedule.

Thermal Conductivity

The thermal conductivity of the composite has bearing upon the amount of heat which may be absorbed by this component in the firing time. The temperature limits computed above range from essentially complete to negligible conduction into the composite. The actual situation lies somewhere between these limits. It is clear, however, based upon the computed temperature limits, that thermal conductivity plays a subordinate role to heat capacity in limitation of working temperatures. Certainly increase of the thermal conductivity of the composite material would not alter the conclusions of the previous section since these were derived on the basis of complete conduction into the composite. Thermal conductivities of typical composite materials are usually low compared to steel and this would influence barrel temperature levels in the direction of the maximum temperatures computed above. While composite thermal conductivity is low, there is, nonetheless, significant thermal mass contribution associated with it acting to reduce its required operating temperatures. This is illustrated in Figure 8 which shows the influence of composite thermal conductivity on required operating temperature for a candidate tube design configuration which would exceed desired weight reduction goals. From this figure we note that while there is a rather rapid reduction in required operating temperature with increase of thermal conductivity, its influence diminishes substantially with increase beyond that typically associated with composite plastics. The benefit to be derived by modification of the composite to improve its conductivity, therefore, appears questionable. We consider the case whereby thermal conductivity might be increased by addition of conductive metallic chips. In light of the composite wrap requirements and the need for external pressurization in curing, it is most likely that such chips would act to improve conductivity through conductance

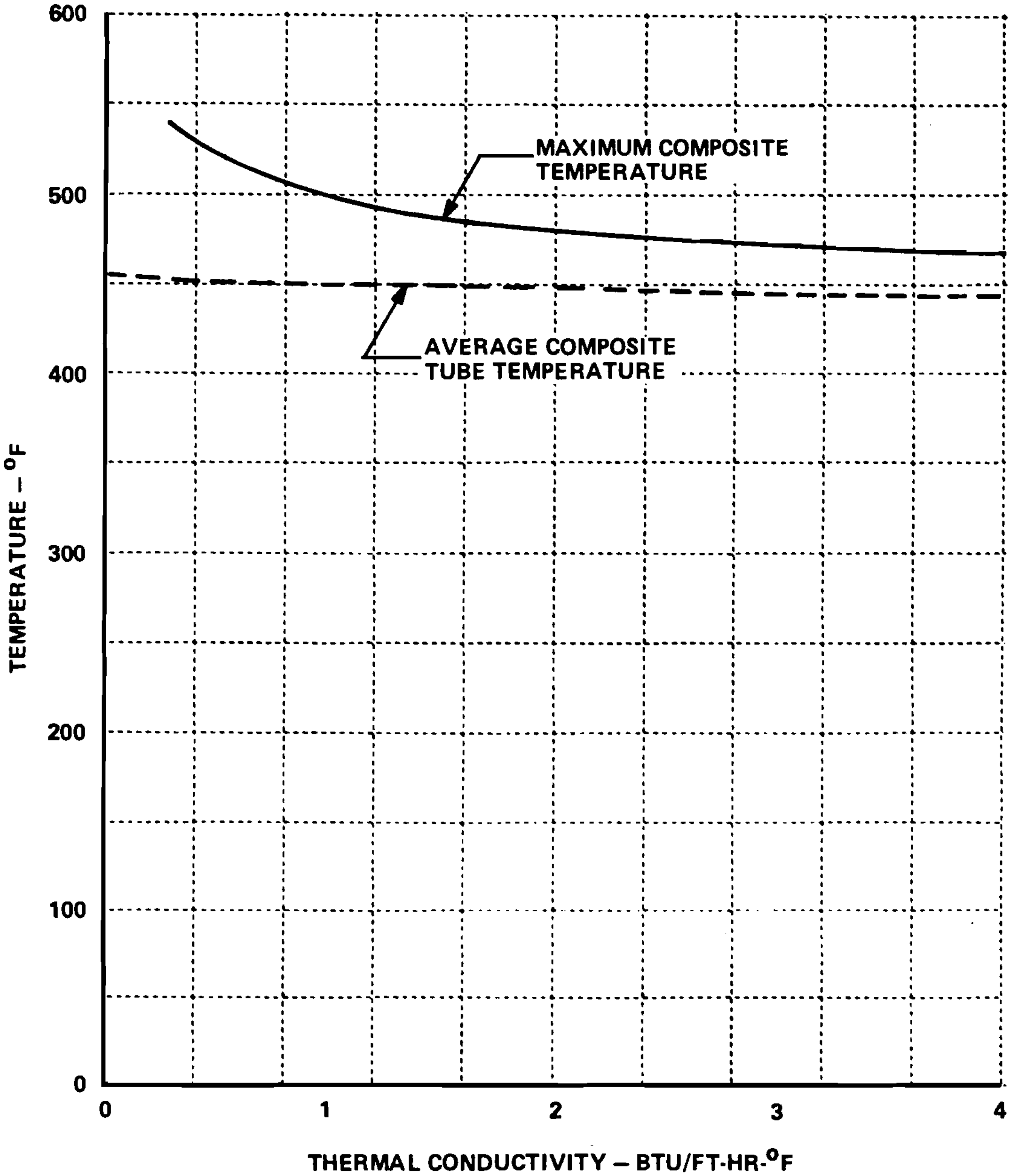

Figure 8. Effect of Composite Thermal Conductivity on Composite Temperatures at 63 Rounds (75 inch Station Design No. 1)

change in series with the composite material. The effective thermal conductivity would be given by:

$$K_{EFF} = \frac{K_m K_c}{X_m K_c + (1-X_m)K_m} \tag{14}$$

where, X_m is the volume percentage of metallic chips

and $(\ )_m$, $(\ )_c$ refer to metal and composite respectively.

Because $K_m >> K_c$ equation (14) reduces to

$$\frac{K_{EFF}}{K_c} \approx \frac{1}{(1-X_m)} \tag{15}$$

Hence, the effective conductivity increases inversely with the fraction of composite. The effective density of the metallic chip modified composite is given by:

$$\rho_{EFF} = X_m \rho_m + (1-X_m)\ \rho_c \tag{16}$$

or $$\frac{\rho_{EFF}}{\rho_c} = (1-X_m) + X_m\ \frac{\rho_m}{\rho_c} \tag{17}$$

Because ρ_m/ρ_c is usually greater than 1, more thickness of modified composite would be needed to attain a given weight reduction. Since the effective conductance of the composite depends upon thermal conductivity and thickness in accord with

$$U_{EFF} \sim \frac{K_{EFF}}{\delta}$$

and the required composite thickness for any weight reduction is inversely proportional to $(\rho_s - \rho_{EFF})$. An approximate relation for conductance is given by

$$U_{EFF} \sim K_{EFF} \left(\rho_s - \rho_{EFF}\right)$$

$$\sim \frac{K_c}{(1-X_m)} \left(\rho_s - \rho_c\ (1-X_m) - X_m\ \rho_m\right) \tag{18}$$

Thus,

$$\frac{U_{EFF}}{U_c} = \frac{\left[\rho_s/\rho_c - (1-X_m) - \rho_m/\rho_c\, X_m\right]}{\left(1-X_m\right)\left(\rho_s/\rho_c - 1\right)} \tag{19}$$

Table 3 illustrates values of U_{EFF}/U_c for given volumetric percentages of steel, aluminum, and magnesium chip addition to the composite:

TABLE 3

Effect of Metal Chip Addition on
Relative Composite Conductance

Volume percent metallic chip	U_{EFF}/U_c		
	Steel	Aluminum	Magnesium
10	1.0	1.09	1.11
20	1.0	1.21	1.25
30	1.0	1.36	1.48
40	1.0	1.42	1.66

Based upon Table 3 and Figure 8, it is clear that limitation of required composite operating temperatures through metallic chip modification of the composite is fruitless. Furthermore, such modifications would no doubt serve to weaken the structure, and increase fabrication costs, and could actually increase required working temperatures as a result of possible reductions in heat capacity associated with the increased total volume of composite needed.

Cook-off

One possible limitation to attainment of maximum weight reduction through use of the composite to its full working temperature is the need to minimize, to the extent possible, cook-off of propellants or high explosives following insertion of the round into the heated tube. The cook-off threshold of typical propellants is about 425°F and is somewhat higher for explosives. Hence, temperatures exceeding this level create greater cook-off hazards. The total round length is about 40 inches. Thus, the first 40 inches of tube would best be maintained at a temperature little greater than that which now exists in the current tube. This is about 375°F after 63 rounds. From this point to the position of the evacuator, however, the tube temperature may be permitted to reach the full short-term working temperature of the composite or 600°F in the case of polyimide-carbon. There may, however, be no absolute need to maintain similar cook-off performance in the cannon and therefore some marginal increase in allowable breech temperatures may be permitted with attendant tube weight reduction.

Tube/Composite Interfaces

The best mechanical tube design would have as few axial interruptions in composite structure as possible. The major strength element in the composite is the fiber. Interruptions in fiber, therefore, result in a weakening of the structure. Where the composite material is terminated axially, the usual procedure is to provide a scarf joint to better resist the separation loads. Selection of natural breaks or steps in tube for termination of composite is more desirable because no separation load would exist.

The rather low shear strength of composite materials along the laminate, coupled with stress concentrations at notched areas along with their low impact resistance, precludes use of the composite in the area of the interrupted threads at the breech. For this reason, at least one joint along the tube is required. Cook-off requirements suggest that this be at a location approximately 40 inches from the breech face although this requirement may be violated if greater weight reduction is imperative.

Thermal Mass Distribution and Materials

With the elimination of thermal absorption and/or loss as possible means for minimization of required working temperatures, one must look toward maximization of allowable working temperature through judicious selection of composite material type along with its application confined to areas of the tube having minimum basic temperatures.

Reviewing available resin types we find little hope for use of common high temperature epoxy with use temperatures to 350°F. Tube operating temperatures are bound to exceed this level under desired firing schedules. Bis-Mal-Imides (BMI) systems with use temperatures to 450°F offer improved weight reduction benefit but will not fully achieve the desired weight reduction goals. Poly-Phenol-Sulfide (PPS) - carbon fiber systems applied as thermo-plastic films also possess improved but insufficient high temperature performance. The polyimide-carbon composite systems appear to offer the highest near term potential for the present application. Discussions with manufacturer/fabricators of this material indicate it to withstand exposure to temperatures in excess of 600°F with little deterioration of mechanical performance. Pre-preg fabrics, tapes, and roving can be produced at costs ranging from 55 to 450 dollars per pound, depending upon the fiber utilized. The cost of the material is dominated by the cost of fiber. The tensile strength for these materials in the fiber direction may exceed 200 KSI even at temperatures in excess of 600°F. The tensile modulus is governed by the fiber type and orientation and can be made directionally to exceed that of steel albeit at high cost per pound.

Based upon the foregoing analysis, it was deemed most prudent to pursue M68 tube designs based upon use of polyimide-carbon composite material placed rearward of the bore evacuator. Here, the computed temperatures are sufficiently below the working temperature of the composite that meaningful weight reductions may be obtained.

Autofrettage Requirements

The current M68 tube is ram autofrettaged to increase fatigue life. Its fatigue life is now about 1000 rounds with failure apparently governed by crack propagation from the outer breech interrupted thread area to the chamber bore.[5] The autofrettage technique and fixtures utilized in the current tube are the result of considerable research and development over a number of years. Full autofrettage of the composite tube is believed necessary if fatigue life is to be maintained. As a consequence of material mechanical property differences and sizes, it is doubtful that the same techniques and tooling may be used to autofrettage the composite tube. This would need be a subject of future study, but we feel that a composite tube can be autofrettaged in similar fashion to that now in use at Watervliet Arsenal with due account taken of the composite nature of the structure. For purposes of this work, Calspan's simplified finite element thermal/stress routine includes relations for "full" autofrettage residual stresses. These were developed by modification of Nadai's classical treatment of a partially yielded tube wall.[6]

We note that the requirement for full tube autofrettage most likely will require external machining of the bearing surfaces of the tube to maintain concentricity. Because a portion of this bearing surface (that positioned within the tank mount) would be composite, the machinability and load bearing characteristics of the composite material must be considered in the final composite tube design. Discussions with suppliers of polyimide-carbon pre-preg materials suggest it to possess excellent machinability so that this should pose no basic difficulty.

Interfacial Bond Requirements

A reduction of tube weight has influence on velocity of the recoiling mass. For the tank installation, the tube makes up the majority of this mass and significant reduction in its weight may require changes in the recoil mechanism to adjust for increased recoil velocity. These adjustments are expected to be minor, however, and should not hinder implementation of the composite tube concept.

The influence of recoil on the interfacial bond between steel and composite material is inconsequential when compared to the stresses at the bond associated with curing requirements for the material.

The shear stress at the bond due to recoil is given by:

$$\tau_1 = \frac{M_c}{M_T} \frac{A_B}{S_c} P_c \qquad (20)$$

in which:

M_c is the mass of composite

M_T is the total composite tube mass

A_B is the bore area

S_c is the shear area for composite

P_c is the maximum chamber pressure

When we note that $M_c/M_T \simeq .1$ and S_c/A_B needs to be of the order of at least 70 to obtain a 10% weight reduction, the recoil shear stress is less than 0.0014 P_c. With a maximum chamber pressure level of 60,000 psi, S_c computes to be less than 85 psi.

By contrast, for any practical layup, the axial shear stress at the bond associated with cooling from the cure temperature is given by:

$$\tau_2 = \frac{(\alpha_s - \alpha_c)\ A_s A_c E_s E_c\ \Delta T_{cure}}{S_c(A_c E_c + A_s E_s)} \tag{21}$$

where

α_s, α_c	are respective thermal expansion coefficients for steel and composite
A_s	is the steel cross-sectional area
A_c	is the composite cross-sectional area
E_s, E_c	are respective elastic moduli for steel and composite
S_c	is the shear surface area
ΔT_{cure}	is the temperature drop from cure

A single cylindrical shelled composite tube would require:

$$A_s \approx A_c$$

$$E_s \approx E_c$$

$$S_c/A_s \approx 50$$

in order to meet weight/strength/stiffness goals. Furthermore, as is suggested later in this report, a majority of the fiber need be in the axial direction. Thus, $\alpha_s >> \alpha_c$ and

$$\tau_2 = \frac{\alpha_s E_s\ \Delta T_{cure}}{100} \tag{22}$$

Inserting typical values for steel and assuming $\Delta T_{cure} = 550°F$, the shear stress at the bond due to cooling from cure could be as much as:

$$\tau_2 \approx \frac{6 \times 10^{-6}(30 \times 10^6)(550)}{100} \approx 1000 \text{ psi}$$

This shear stress must be borne by the adhesive at the composite/metal interface.

Significant tensile stress at the bond due to cooling from the cure temperature may also be developed as a consequence of thermal expansion differences between steel and composite.

This interfacial radial tensile stress is given by:

$$\sigma_r = \frac{(\alpha_s - \alpha_c)\ \Delta T_{cure}}{\frac{1}{E_s}\left[\frac{(D_i^2 + D_b^2)}{(D_i^2 - D_b^2)} - \mu_s\right] + \frac{1}{E_c}\left[\frac{(D_c^2 + D_i^2)}{(D_c^2 - D_i^2)} + \mu_c\right]} \qquad (23)$$

Because α_c is probably no more than 1/2 α_s, and we require $E_s \approx E_c$, this equation simplifies to:

$$\sigma_r = \frac{\alpha_s E_s A_s A_c\ \Delta T_{cure}}{\Pi D_i^2\ A_{TOT}} \qquad (24)$$

As above, A_s needs to be about equal to A_c to obtain the needed weight reduction goal. Then we have the approximate relation:

$$\sigma_r = \frac{\alpha_s E_s\ \Delta T_{cure}}{2}\ \left[1 - \left(\frac{D_b^2}{D_i^2}\right)\right] \qquad (25)$$

Inserting typical values for steel and taking $D_i \approx 7$ inch as the diameter to the composite/steel interface, we get:

$$\sigma_r = 14.28\ \Delta T_{cure}$$

$$= 14.28\ (550) = 7850 \text{ psi}$$

as the radial tensile stress on the composite/steel interfacial bond following cooling from the cure temperature. This stress must be borne by the cured resin at the interface. Little, if any, benefit would be derived from the matrix fibers being that the thermal forces are attempting to "pull" the interface apart as a result of the radial contraction of the steel.

Conventional resin binders do not exhibit a high degree of adhesion to steel, especially in shock loading situations as exist in gun firings. Thus, the direct application of pre-preg tapes, filaments, or fabrics to steel is not advised. A surface preparation and adhesive application prior to pre-preg layup is necessary. This adhesive must of necessity withstand temperatures of a level consistent with that of the composite material (600°F for a polyimide-carbon matrix). Additionally, practical utilization of such adhesives would demand that they be cured in situ during the curing of the composite layup. This may be difficult to achieve in practice due to the tendency of the pre-preg to absorb adhesive resin. An appropriate laminate-to-metal bonding technique for the suggested polyimide-carbon system needs development before any practical composite tube of this type can be fielded. This may be a subject requiring considerable developmental effort in view of the rather high stresses at the bond interface indicated above. These are likely to be beyond the capability of adhesives or pure resins. Hence, there is some question whether composite material applied to steel is a feasible concept for this gun tube application. Certainly, the computed cure stresses are not favorable.

Composite Tube Configurations

In keeping with the ideas presented above, our analysis of the design constraints imposed upon the M68 tube design results in the conclusion that the weight reduction goals sought can most practically be realized by redistribution of tube mass through application of composite material solely in regions rearward of the bore evaluator. Figures 9 and 10 illustrate conceptual tube designs which can exceed the 10% weight reduction goal of the present work. For these use of composite material is restricted to the location from 25 to 103.5 inches as measured from the breech. This is essentially from the origin of rifling to the position of the bore evacuator. Forward of the bore evacuator no modification is recommended, although some <u>increase</u> in diameter or length can be tolerated while still resulting in a net tube weight reduction if maximum use of composite is made. For example, the tube design of Figure 9 would result in a net weight reduction of 257 lb or more than 15% of the present tube weight.

Other designs as shown in Figure 10 can result in greater weight savings while maintaining temperatures below the maximum operating level for polyimide resin composite (600°F). Design number 2 results in a weight savings of 285 lb. Design number 3 appears to be near a minimum weight design for this temperature and results in a weight savings of 326 lb. This is approximately 19% of the current tube weight.

All of these conceptual designs by necessity maintain at least the same outer envelope of the present M68 tube throughout. It is of interest to note that the 326 lb weight savings due to use of composite could permit an increase of tube length of more than 6 ft without increase in weight over that of the present tube. This may be of importance where enhanced gun performance is desired, and may be considered as a future alternative design.

The temperatures associated with continuous firing of M456 ammunition at 8 rounds per minute for designs nos. 1 and 3 are given in Figures 11 and 12. Inspection of Figure 12 suggests that some additional material may yet be removed from the tube without exceeding the 550°F working temperature. While this is true, it also would entail use of unusual contours on the outer steel core to obtain optimum temperature distribution. This is not deemed worthwhile in view of the rather minor associated weight reductions. Calspan considers the weight reduction afforded by design no. 3 to be a near maximum for presently available composite materials. Furthermore, Design no. 3 requires application of composite to tapered outer tube contours. This may be difficult to implement in practice with use of other than filament winding techniques.

Composite Structure Considerations

The potential for use of composite material in place of steel on the M68 cannon must also be assessed with due account taken of practical laminate constructions evolving from available impregnated graphite fiber configurations. Various wrap constructions should be considered ranging from simple filament winding to combinations of helix tape pre-preg with bi-directional pre-preg cloth.

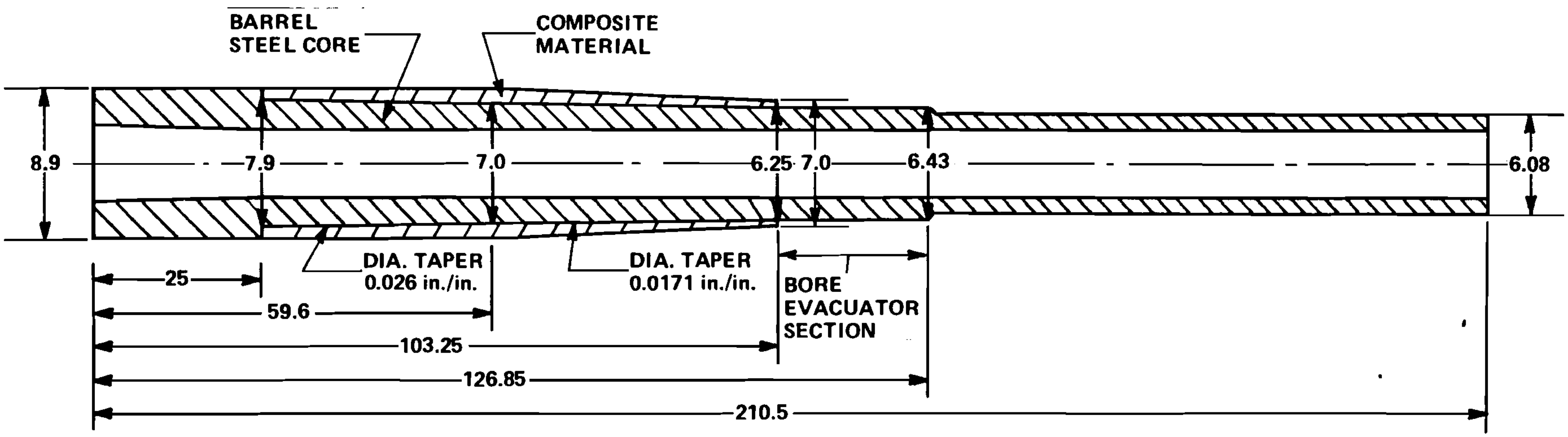

Figure 9. Preliminary Composite Tube Design

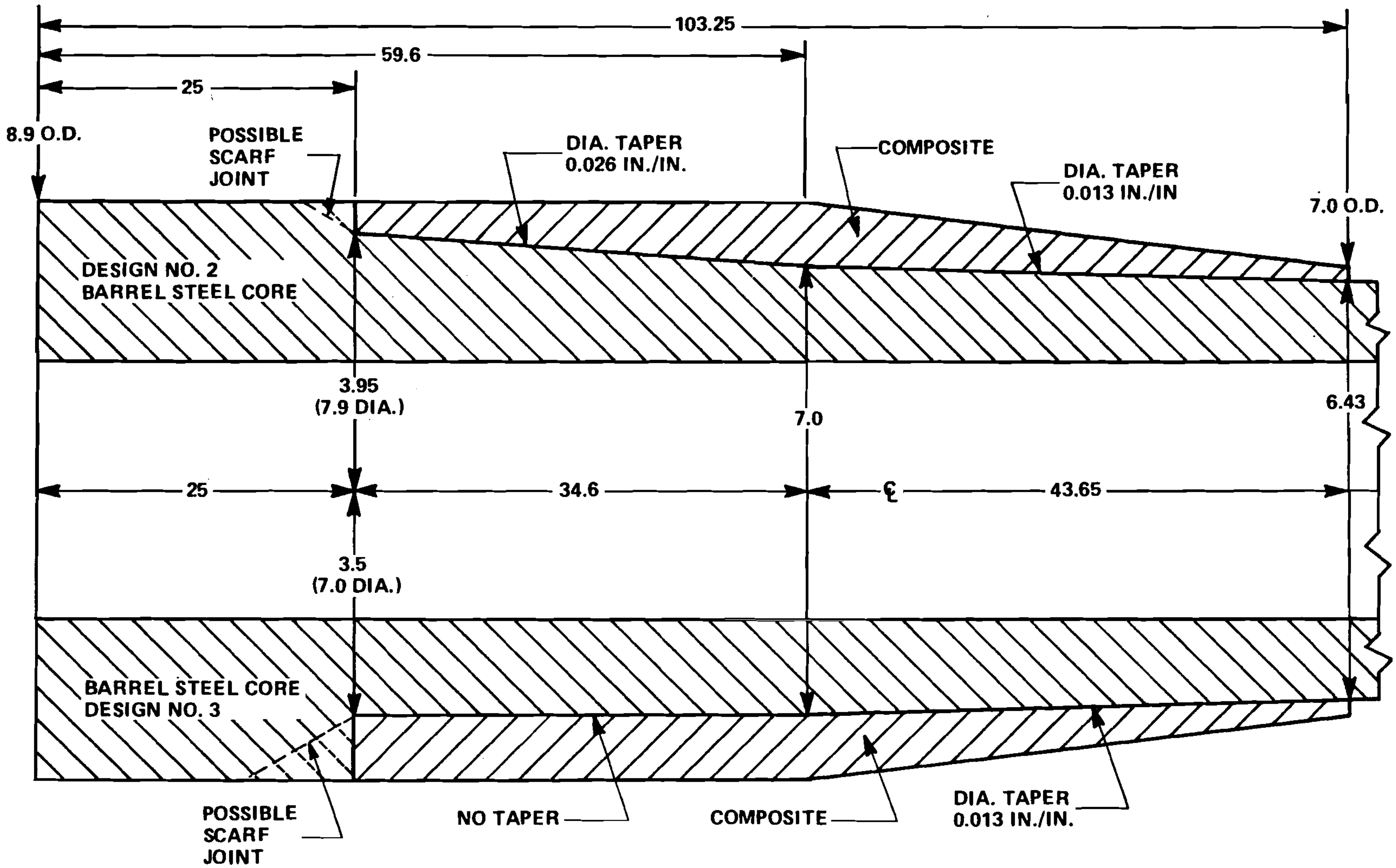

Figure 10. Supplementary Composite Tube Designs (Top-No. 1, Bottom-No. 3)

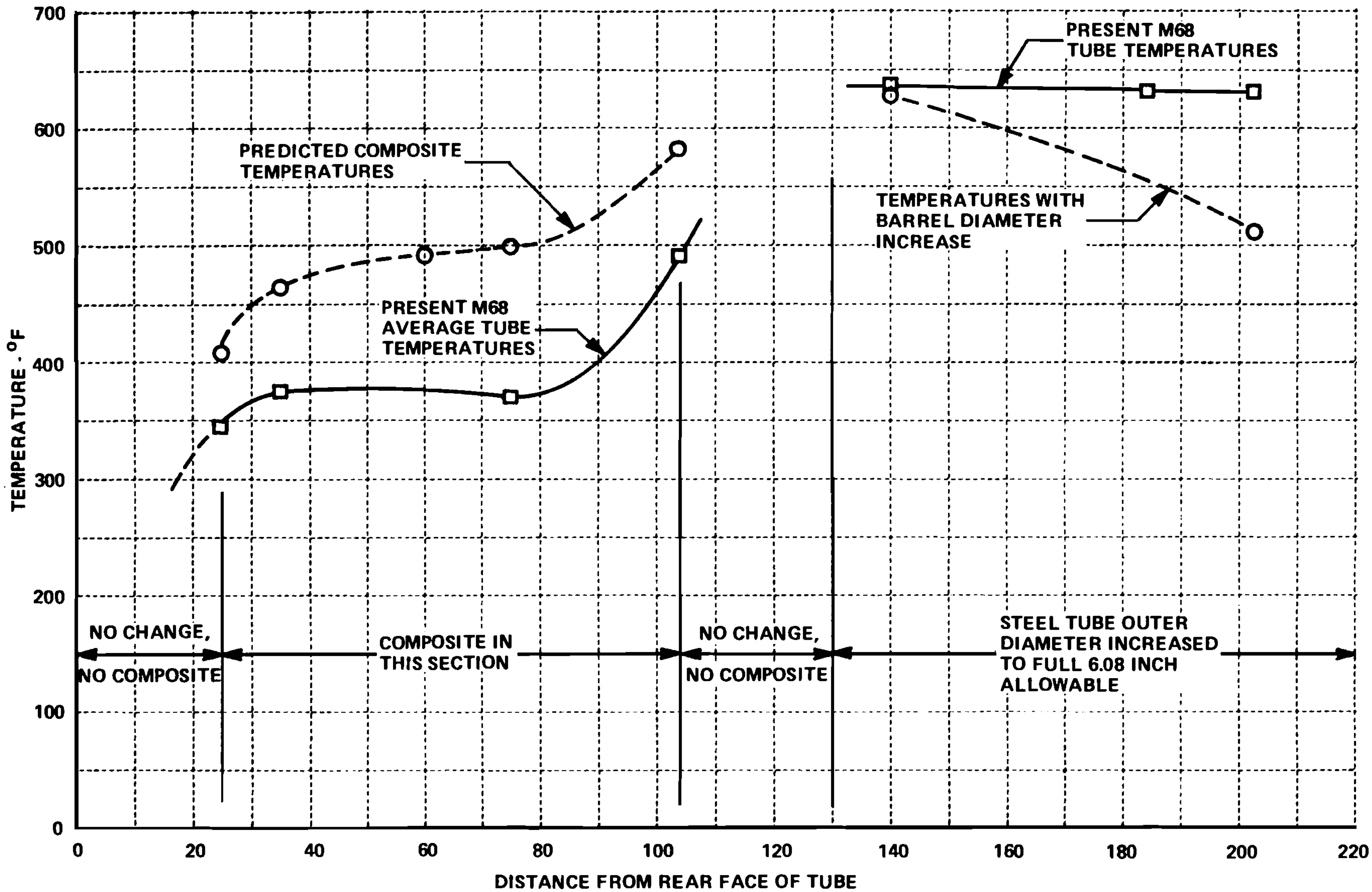

Figure 11. Predicted Temperatures at 63 Rounds for the Preliminary Composite Tube Design of Figure 1

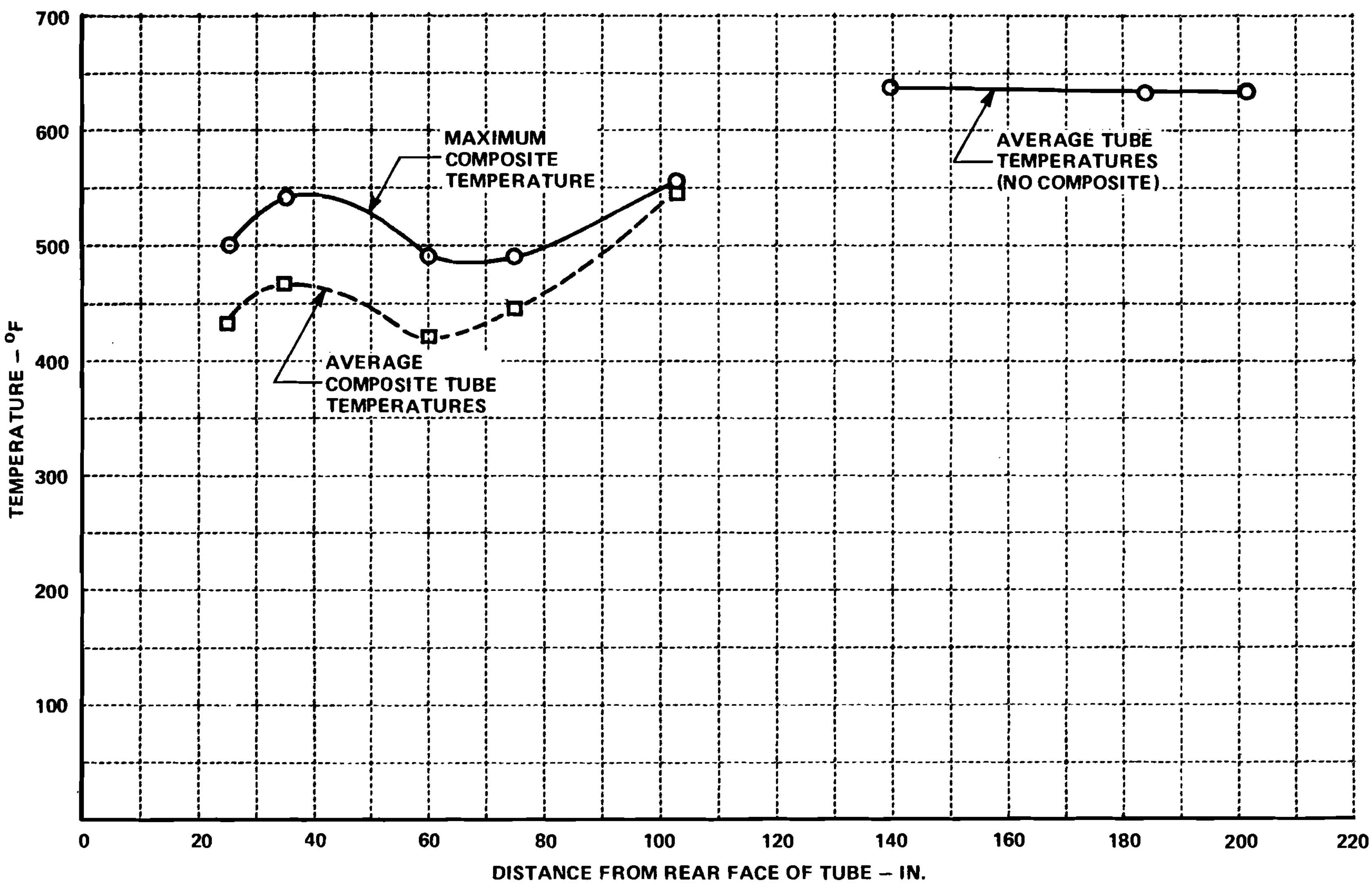

Figure 12. Temperatures for "Minimum" Weight Composite Tube Design No. 3

The use of unidirectional tape would permit rather controlled development of mechanical properties. Depending upon the helix angle angle of wrap, one would expect that variations in hoop and longitudinal strength can be produced as desired. Because the tape cannot be stretched more than a few percent, however, there is a rather specific relationship between helix angle and diameter for any tape width. Figure 13 illustrates this relationship. We also note that the hoop and longitudinal strengths are given respectively by:

$$\sigma_y = \sigma_T \sin^2 \theta \tag{26}$$

$$\sigma_x = \sigma_T \sin^2 \theta \tag{27}$$

By inspection, one may observe that significant tape width is needed in order to reduce the helix angle to the point where meaningful longitudinal strength is obtained. For example, at an angle of 45 degrees, the hoop and longitudinal strengths are equal to 0.5 σ_T. With a tube core diameter of about 7 inches to be wrapped, the tape width must be in the neighborhood of 16 inches. This would permit some overlap. Note that wider tape needs to be used if this angle is to be maintained as diameter increases; otherwise the angle would increase, thus leading to lowered longitudinal strength and stiffness. Because such tape widths can be obtained commercially, this method of layup is feasible.

The moduli in the hoop and longitudinal directions are more strongly dependent on the wrap angle, viz.:

$$E_y = E_T \sin^4 \theta \tag{28}$$

$$E_x = E_T \cos^4 \theta \tag{29}$$

The actual tape modulus can be very high when using graphite (carbon) fiber, but probably will not exceed 40 x 10^6 unless very expensive fiber is used. A longitudinal modulus approaching that of steel ($\approx 30 \times 10^6$) will therefore be difficult to produce requiring rather shallow wrap angles, say about 20 degrees. This would, however, require use of very wide tape and would present difficulty in fabrication. Furthermore, very significant loss in both hoop strength and modulus would accompany application at this angle alone. Through application of various tape widths/overlaps, one could adjust hoop strength vs. longitudinal modulus over wide ranges; but application of the material would become tedious, difficult, and costly. Similar problems accrue with use of filament or roving. In addition, the discontinuities presented at the end terminations may make filament wrap difficult to apply, although machine application would lower manpower costs.

Because both longitudinal stiffness and hoop strength are needed in the composite layup, angular wrapping methods appear unattractive for this application. Rather, we suggest combinations of orthogonal wraps consisting of uniaxial longitudinal tape with intermediate filament windings or fabric pre-pregs with intermediate longitudinal tape. The tape/filament technique

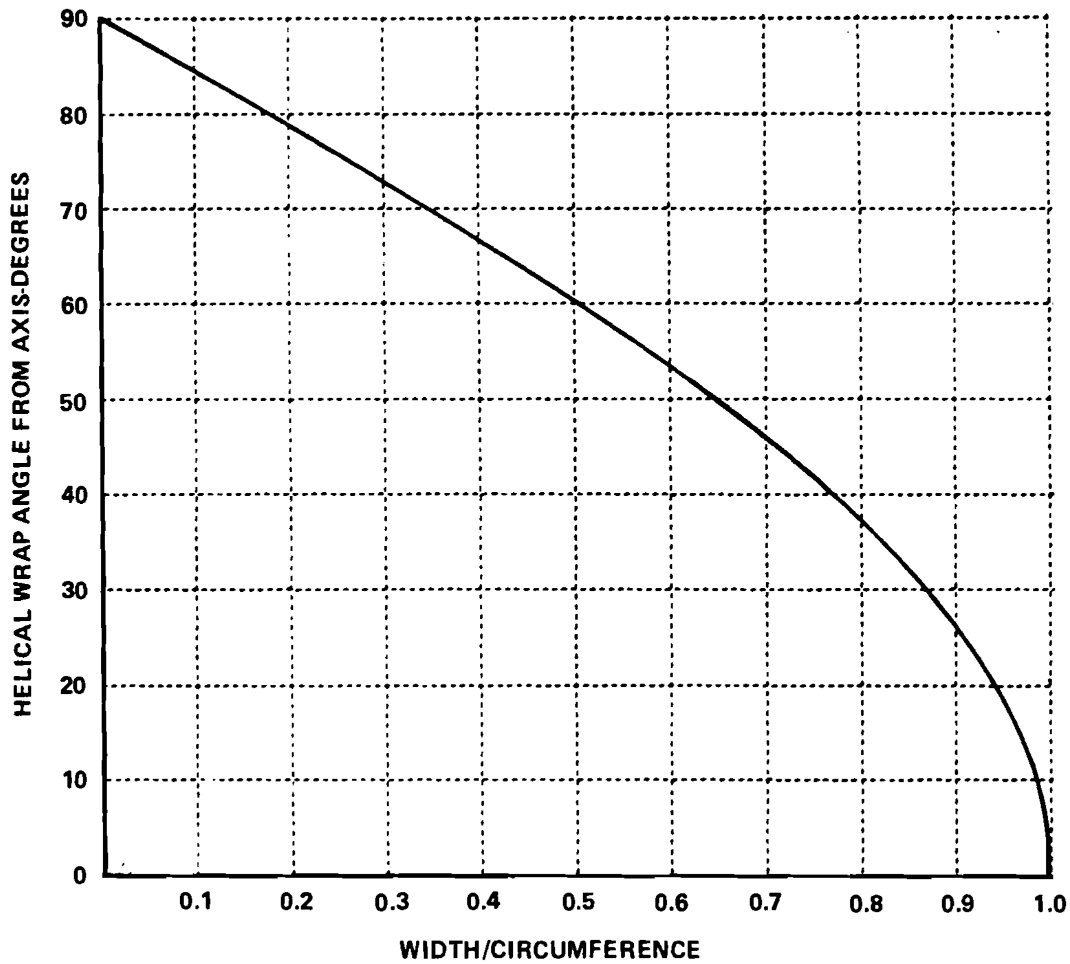

Figure 13. Wrap Angle as a Function of Width-to-Circumference Ratio

could result in optimal properties by suitable interspersion of tape/filament wraps. However, non-uniform cross-sections would be produced. Fabric pre-pregs can be engineered to optimize hoop strength and longitudinal stiffness by appropriate adjustment of the ratio of warp-to-fill yarns and their size. With either structure, for equal volume of material, the stiffness can be made greater than can practically be achieved in a helical tape wrap. Fabric or tape is best applied to a cylindrical rather than tapered surface. For this reason, the previous conceptual designs based for the most part on temperature must be altered somewhat. Figure 14 illustrates a suggested composite tube concept which attains the desired 10% weight reduction goal while minimizing fabrication problems. Here, the percentages of axial and longitudinal fibers can be adjusted to result in a judicious compromise of strength/stiffness for the tube. We must note that unless very expensive fabrics are to be used (>300 dollars/lb), either strength or stiffness must be compromised to some degree compared to that of the existing steel tube. Observe the resulting strength/stiffness characteristics as a function of the ratio of longitudinal to hoop fiber weight. These are shown in Table 4 for a typical moderate-to-high priced graphite fiber. We find that, within the volume constraints of the existing tube, a longitudinal modulus equivalent to that of steel ($\approx 29 \times 10^6$ psi) is only obtained at full sacrifice of hoop modulus and strength (i.e., no fibers in the hoop direction). As we increase the percentage fiber in the hoop direction, more and more longitudinal stiffness is lost, while hoop strength and modulus is increasing. It is clear, therefore, that some compromise in stiffness/strength must be made if the desired weight savings are to be realized.

It is difficult to generalize regarding all aspects of composite structure design and corresponding stress factors. We do, however, observe that a lowering of the hoop modulus for the composite naturally leads to a lowering of its strength requirement in that more stress is borne by the steel core portion of the tube. This is illustrated in Table 5 where computed stress factors for the 75-inch station of conceptual Design no. 1 are given at 65 rounds fired. These are the combined effects of autofrettage, composite cure, thermal, dynamic axial, and pressure stresses. As expected, the composite hoop stress reduces with hoop modulus, whereas the interfacial combined stress in the steel increases. The lowered combined stress at the bore surface is not fully understood, but is believed due, in part, to the altered autofrettage stress pattern associated with use of the lower hoop modulus material. In any event, we can see that very low hoop modulus material may be used without overstressing the steel or composite components. There is, of course, some added radial strain associated with the lowered hoop modulus and this could have some bearing on the ballistic performance of the gun if projectile band leakage is induced. Evaluation of such performance effects is beyond the scope of the present effort and is simply mentioned as further justification for use of some hoop wrapping, which is needed in any event to minimize the possibility of an axially progressing tear in the composite. Although computations suggest little requirement for hoop wrappings, in an effort to maintain some measure of homogeneity in the composite structure, we recommend that at least 20% of the fiber wrap be in the hoop direction. This could result in a rather minimum loss in axial stiffness with a possible hoop strength above 35,000 psi (see Table 4), if moderate-to-high priced fiber is used.

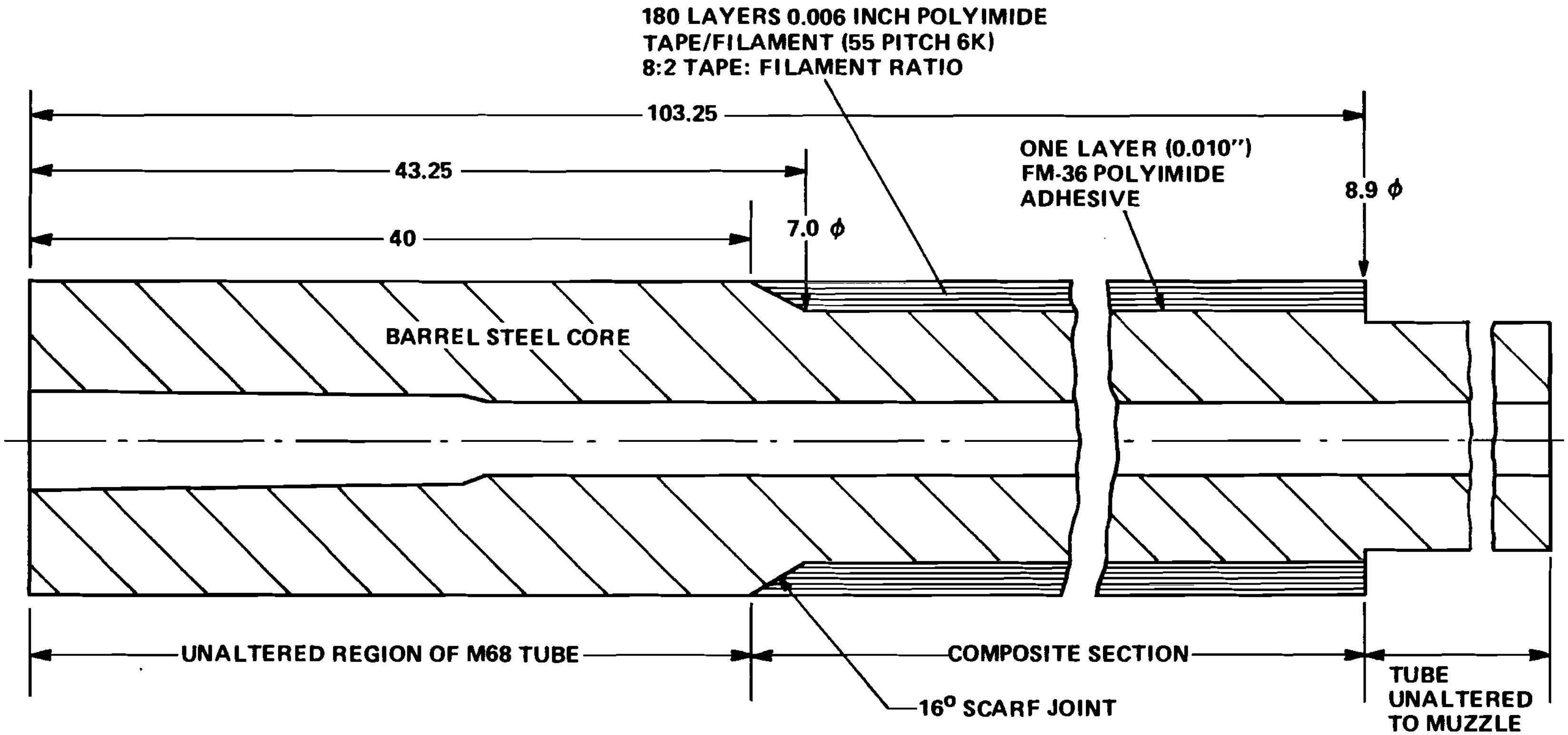

Figure 14. Suggested M68 Composite Tube Design Concept

TABLE 4

Effect of Axial-to-Hoop Fiber Weight Ratio on Mechanical Properties

Axial/Hoop Fiber Weight Ratio	Effective Modulus		Tensile Strength	
	Axial	Hoop	Axial	Hoop
%	msi	msi	ksi	ksi
100/0	29.5	<1	190	<10
90/10	26.5	3.0	170	20
80/20	23.5	6.0	150	40
70/30	20.5	9.0	130	60
60/40	17.5	12.0	110	80
50/50	14.75	14.75	95	95
40/60	12.0	17.5	80	110
20/80	6.0	23.5	40	150
0/100	<1	29.5	<10	190

Fiber Properties:

Modulus = 55×10^6 psi

Strength = 350,000 psi

60% by weight of composite

54% by volume of composite

TABLE 5

Effect of Hoop Modulus on Computed Composite Tube Stress Factors at 65 Rounds Fired

Hoop Modulus msi	Combined Stresses in Steel Core psi		Stresses in Composite - psi		
			Hoop	Initial Cure Stresses	
	Surface	Interface	Interface	Hoop	Radial
29	96,700	57,800	51,000	-52,700	10,400
25	95,400	60,400	46,600	-47,200	9,300
20	93,600	64,100	40,000	-39,600	7,800
15	91,700	68,500	32,300	-31,200	6,100
10	89,500	73,900	23,400	-21,900	4,300
5	87,200	80,400	12,800	-11,600	2,300

Composite Tube Fabrication

Discussions with composite materials suppliers/fabricators indicate that fabrication of a composite tube of the desired size using polyimide/graphite pre-pregs will not be an easy task; but is at this time virtually the only composite system which can meet the temperature requirements. Among the industry contacts were:

1. Fiberite Corporation
   Winona, Minnesota
   (Mr. Carl Smith)
   (507)454-3611

2. Philips Petroleum
   Bartlesville, Oklahoma 74004
   (Mr. Tim Murtha)
   (918)661-7724

3. Rhone Poulenc, Inc.
   Monmouth Junction, NJ
   (201)846-7700

4. Gulf Oil Industrial
   Chemical Division
   Houston, TX
   (713)754-4183

5. Upjohn Company
   Polymer Chemical Division
   LaPorte, TX
   (Mr. Tilak Shah)
   (203)281-2700

6. Freedom Manufacturing
   Fall River, Massachusetts
   (Mr. M. Leary)
   (617)673-5865

7. CIBA-GEIGY Corporation
   California Division
   (Dr. Ken Berg)
   (714)963-9900

8. U.S. Polymeric
   Santa Anna, California
   (Mr. Mark Ferris)
   (714)549-1101

9. Fiber Materials, Inc.
   Biddleford, Maine 04005
   (Mr. M. Vitturioso)
   (207)282-5911

10. Lunn Industries, Inc.
    Wyandanch, New York 11798
    (Mr. Jeffrey Ferris)
    (516)643-8900

We found that the cure temperature of the polyimide is approximately 600°F and volatiles are very high. Attainment of desired strength requires cure at pressure near 200 psi which is above that available in most autoclave apparatus. Difficulty in elimination of volatiles from the matrix at these pressures tends to result in a porous structure, such porosity increases with cure thickness so that multiple wrap/cure/post-cure cycles are needed to build thickness and attain properties. Shifting of the fabric position relative to the tube must be minimized to avoid post-cure separation at the end terminations (scarf joint). This can be severe when we consider a possible differential expansion between tube and composite of 0.187 inches over 60 inches of length. The need to apply the material in stages at the same cure temperature might lead to axial buckling of the thinner first layer. Certainly, the thermal compressive stress will be higher.

Layup and cure procedures recommended by NASA for LARC 160 polyimide are as given in Tables 6 and 7. These procedures have been found to yield dense uniform structures. Because single step cured thicknesses above 0.5 inches were not advised by suppliers and a cured thickness approaching one inch is needed to obtain desired weight reduction goals, at least two layup/cure cycles are recommended. Assuming as above a 4/1 longitudinal/hoop fiber weight ratio, a possible layup using tape/filament approximately 0.006 inch thick is 16 layers

TABLE 6

Press Cure Lay-Up Procedure LP-8

I. Tool Plate

II. FEP Film or Release Agent

III. Prepreg Lay-up

IV. Porous Teflon

V. Four Plies 1581 Glass

VI. Vacuum Bag

TABLE 7

Press Cure Molding Procedure M-8

Instructions for Laminate Preparation
Prior to Molding

1. Debulk prepreg lay-up under 2" - 4" Hg.
2. Maintain vacuum and heat the prepreg lay-up to 325°F $\pm$ 5°F at a rate of 5°F/min
3. Hold for 1 hour at 325°F and 2"-4" Hg.
4. Cool under vacuum to room temperature and remove

MOLDING PROCEDURE

I. Preheat mold and press to 400°F $\pm$ 5°F.
II. Charge mold with debulked laminate, load press.
III. Apply kiss pressure only.
IV. Raise temperature from 400°F to 525°F @ F/Min.
V. At 525°F add 200 psi over a one minute period.
VI. Hold at 525°F and 200 psi for one minute.
VII. Remove pressure to 0 psi for 15 seconds, then reapply 200 psi.
VIII. Continue raising temperature @ 5°F/min to 600°F $\pm$ 5°F.
IX. Hold under pressure at 600°F for 2 hours.
X. Cool to room temperature under pressure and remove.

of unidirectional tape followed by 4 hoop wraps of pre-preg filament or roving, etc. Nine such layers would achieve desired cure thickness. Greater homogeneity, albeit at greater expense, would be achieved using closer tape/filament spacing, say 8:2 or 4:1.

The use of pre-engineered fabric could reduce labor costs, speed application, and produce even greater uniformity. The ratio of warp-to-fill fibers could be selected in accord with the desired modulus ratio, thus optimizing hoop strength and longitudinal stiffness. Furthermore, for equal volume of material, the stiffness can be made greater than any helical tape wrap. If the fabric can be applied to thickness using a spiral wrap on a cylindrical surface, hoop strength can be enhanced. Continuity of the longitudinal fibers must be maintained by using the widest fabric available, thus minimizing joints and/or overlaps. Fabric widths greater than 60 inches can be obtained in most weave patterns. This is the recommended approach. For either layup procedure, some buckling of the hoop fibers is expected in the curing process as a result of required circumferential length change as fibers are compacted radially by external pressure. Hopefully this will not be severe for the indicated composite tube configuration of Figure 14.

Demonstration Tests

The ability of polyimide/graphite composites to withstand temperatures to 600°F with little deterioration is well documented through manufacturer specifications.* Whether or not the Calspan-suggested approach to alleviation of working temperature levels will limit temperatures as required depends upon our ability to correctly model the tube thermal factors including thermal gradients and heat penetration into the composite. It was hoped that instrumented cylindrical 1/10 models of the tube configuration could be produced and tested to verify the theoretical results. A rather extensive survey of available suppliers was performed with little success in obtaining pre-preg samples having the desired properties for use in a gun tube. High modulus graphite polyimide pre-preg materials are usually engineered for specific applications. In general, suppliers do not carry inventory of these pre-preg materials in stock woven cloth, tape, or filament. The very short shelf life of the resin (about 3-4 mo at 0°F) makes it inefficient for suppliers to maintain a stock supply of these rather costly materials. The cost of any graphite composite will be dominated by the cost of the fiber which can range from 35 to 3000 dollars per pound depending upon fiber size, type, and modulus. For our application, high modulus fiber is desired and this falls in the higher cost per pound range. This further limits availability of stock materials.

Fortunately, Fiberite Corporation was found to have a very limited supply of pre-preg fabric on hand as excess from another production run; specifically:

> Type HMF 1182/78, LARC 160 Polyimide, with standard 3K 30m graphite satin weave.

Several yards of this material were acquired at a cost of about 55 dollars per pound. This is considered to be near minimum cost for this material.

---

*For example, Fiberite Corporation's literature.

Although this fabric was known to have inappropriate mechanical properties for our application, it was felt that its use would provide valuable information regarding the feasibility of application of this type of resin system to a gun tube.

The approximate cured properties for the HMF 1182/78 fabric are as given in Table 8 . Layup and cure procedures are as previously given in Tables 6 and 7.

First efforts at producing a polyimide/graphite laminate were directed toward simple disc type layups cured in a pressurized autoclave. These were produced with mixed results. At thicknesses of about 1/4 inch, the cured laminates were found to be generally compact, however localized voids could be observed throughout the laminate cross-section at strand intersections. The bond between plys also did not appear adequate as if insufficient resin content or wetting was present. In several attempts with varying compaction techniques, little improvement in quality was achieved, suggesting some possible insufficiency in the pre-preg.

Through these efforts, a problem of much greater concern was exposed; namely, the inability to bond any resin pre-preg to steel directly. We found extremely weak bonds between the cured laminates and steel. This would be intolerable in a gun tube where shock loads are high. Through discussions with Mr. Robert Carlson of Fiberite, we concluded that virtually any resin pre-preg application would require use of a suitable adhesive at the steel/ laminate interface. A recommended adhesive for polyimide is FM36 supplied by American Cyanimid Corporation. Its cure temperature is approximately 550°F with potential use to 700°F. With considerable difficulty (not being a stock item), a sample quantity of this adhesive in sheet form was obtained along with a recommended metal priming material BR36. Data sheets and recommended methods of application are as presented in Tables 9 and 10.

After several attempts at producing disc laminates in the autoclave, a usable laminate bonded to 4340 steel was produced. This composite specimen was instrumented with thermocouples at the steel-polyimide interface and the outer surface of the polyimide.

The rate of heat penetration through the polyimide laminate was determined by subjecting the exposed face of the steel to heating from a controlled temperature source. Figure 15 illustrates the test setup. Several tests were performed at various source temperature levels. Figure 16 shows the temperatures recorded at a source temperature of 550°F. The temperature gradient through the laminate is clearly evident as is the time lag for penetration of heat through the 0.235 thick laminate.

Computer analysis of the recorded data was performed and it was found that the temperature responses were essentially duplicated by the computer code using the respective values 0.55 Btu/ft^2-hr-°F, and 35 Btu/ft^3 for the laminate's thermal conductivity and heat capacity per unit volume. The minor deviation of computed values from those recorded at the later times is due to the presence of edge losses in the test which are not present in the code for cylindrical geometry.

TABLE 8

Typical Properties

HMF 1182/78

Pre-Preg Parameters	Data	Test Method
Resin Content, %	37-43	FTM-R-15
Volatile Content @ 204°C, %	8-20	QClC-V-14
Gel Time @ 204°C, Min.	-	FTM-G-2

Cured Laminate Properties	Data			
Test Temperature	75°F	350°F	400°F	600°F
Flexural Strength, KSi	121		115	84
Flexural Modulus, MSi	8.8		9.6	9.0
Short Beam Shear, KSi	9.2		7.4	6.0
Tensile Strength, KSi	97	78		
Tensile Modulus, MSi	11.0	10.5		
Nominal Cured Ply Thickness	.013 inches			
Specific Gravity	1.57			

TABLE 9

Application Procedures BR36/FM36

Surface preparation:

1. Acetone wipe.
2. Rinse in water.
3. Immerse for 15 min. in aqueous solution of Prebond 700 at 2000°F (95°C).
4. Immerse for 20 min. in 4% H_2SO_4 and 4% HCl.
5. Immerse for 15 min. in 12% HNO_3 and 2% HF.
6. Rinse in water.
7. Air dry at 150°F (66°C).

Primer application:

BR36 Primer is supplied at 10% solids and may be applied by spraying. Coat primer on metal to a dried thickness of .0002 to .0003 in. Allow the BR36 primed details a 60-minute air dry followed by a 60-minute oven dry at 250°F (120°C) plus 60 minutes at 410°F (210°C).

Curing procedure:

Press:	60 minutes to 350°F ± 10°F
	60 minutes at 350°F ± 10°F
	Press rate to 550°F ± 10°F
	60 minutes at 550°F ± 10°F
	Cool down to 150°F with 45 psi
Autoclave:	60 minutes to 350°F ± 10°F
	90 minutes at 350°F ± 10°F
	Cool to 150°F ± 5°F with 25 psi, positive pressure and full vacuum

Post cure in preheated circulating air oven at 350°F ± 10°F.

Insert coupons and raise temperature to 550°F ± 10°F in 60 to 70 minutes.

Hold for two hours at 550°F ± 10°F.

TABLE 10

Manufacturers Data Sheets

General:

FM 36 is a modified polyimide adhesive supplied as a supported film with a light weight glass cloth. It is suitable for bonding metal-to-metal, composites and various sandwich structures, serviceable over a temperature range of -67°F (-55 °C) to 550°F (287°C). Because FM 36 contains no metallic fillers, it has good radar transparency.

FM 36 adhesive film and FM 30 adhesive foam are moisture sensitive materials and are packaged in heat-sealed vapor barrier bags with desiccant. It is recommended that the material be warmed to room temperature prior to lay-up and bonding.

Product Description

FM 36 Adhesive Film

Form:	Polyimide adhesive film on a 112 glass cloth	Weight:	0.10 ± 0.010 psi
Volatiles:	Approximately 30%	Shelf Life:	Six months from date of shipment at recommended storage
Color:	Amber	Storage:	Store at or below 0°F (-18°C)

BR 36 Primer

Solids:	10 ± 1%	Shelf Life:	Six months from date of shipment at recommended storage
Color:	Amber		
Thinner:	Diglyme	Storage:	Store at or below 0°F (-18°C)

WARNING: Contains a polyimide resin. May cause allergic skin reaction. Avoid prolonged or repeated contact with skin. Wash thoroughly after handling.

Typical Average Tensile Shear Properties of FM 36 Adhesive Tested with BR 36 Primer and Cured Two Hours at 550°F

Test Condition	Test Temp. °F	Aluminum 1/2 in Large	Aluminum Blister Detection	Titanium 1/2 in Lap
Tensile Shear, psi	-67	3025	2895	-
Tensile Shear, psi	75	2640	2670	2550
Tensile Shear, psi	350	2730	2425	-
Tensile Shear, psi	550	2750	2390	1850
Tensile Shear, psi after 100 hrs @ 550°F	75	-	-	2000
Tensile Shear, psi after 200 hrs @ 550°F	75	-	-	2000

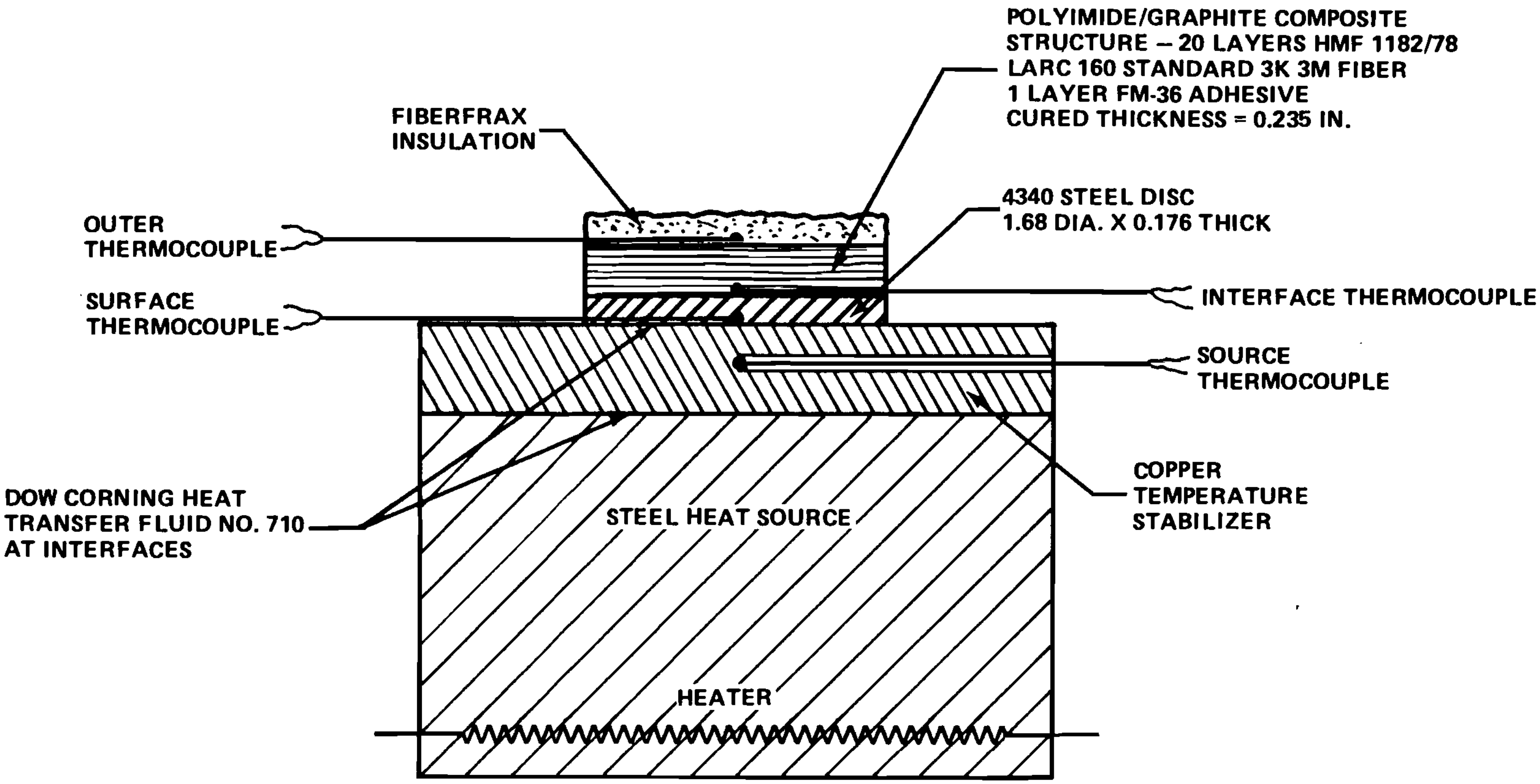

Figure 15. Heat Penetration Test Setup

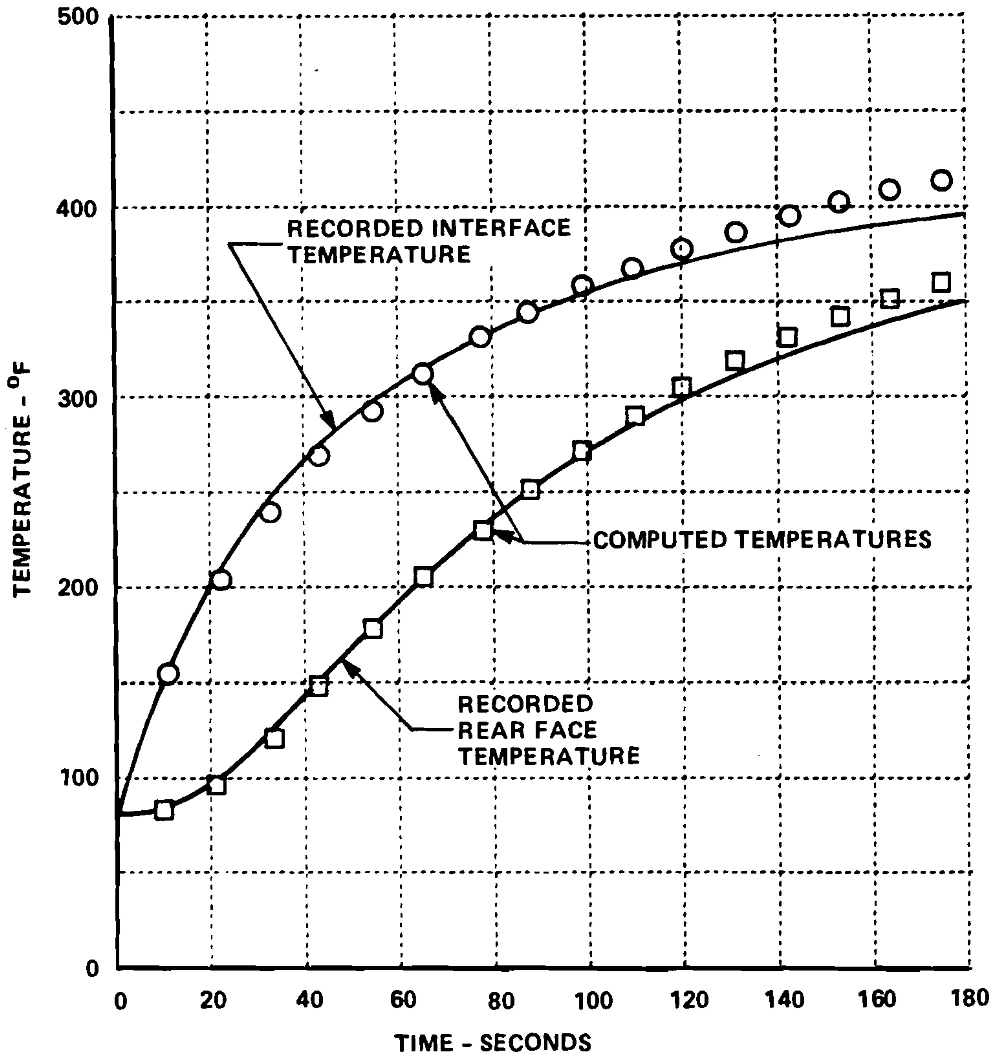

Figure 16. Heat Penetration Through Polyimide Composite Slab Bonded to Steel

The significance of the test toward composite tube design is twofold: first, the ability to compute temperatures and gradients is demonstrated; second, and more important, is that little, with respect to working maximum composites temperature in a continuous 63-round schedule, is to be gained by increase of composite thermal conductivity over that indicated by test. This is shown by reference to Figure 17 which illustrates effect of composite thermal conductivity on required composite working temperature. As discussed earlier and confirmed by test, the more basic limiting factor is the heat capacity per unit volume of the composite which results in greater temperature rise per shot fired. Modification of the composite composition would no doubt result in increased density and weight, thus being counterproductive. Fortunately, it appears that adequate thermal performance can be obtained within the thermal characteristics of unmodified polyimide/graphite composites. Hence, chief emphasis should be placed on mechanics of application and retention of the material to the tube. This appears to be the major drawback of any resin composite system.

Efforts to produce cylindrical test samples similar to that tested above were unsuccessful. Although a number were produced, none exhibited sufficient degree of densification or retention to the steel core. Prepared spiral wraps on 0.7 inch diameter 4340 steel mandrels did not show satisfactory polyimide resin penetration and wetting of the fibers. Discussions with Fiberite personnel could not reveal specific reason for the poor structures obtained. A critical examination of the layup/sealing procedure used to load the cylindrical wrap using gas pressure in the autoclave and subsequent modification of procedures to reduce possible leakage through the aluminum gas barrier failed to result in homogeneous structures. Graphite fibers appeared to be very loosely bonded with considerable voids. In these 1/10 scale samples, the cured cross-section also exhibited considerable distortion as a result of circumferential buckling of the hoop fibers accompanying non-uniform radial compaction of the laminate during the curing process. The consolidation of the laminate was so poor that post-cure machining operations to achieve outer dimensions exposed broken, unwetted, loose, fibers having little resistance against local tooling forces. Finally, essentially no bond between the outer cylindrical laminate and the steel substrate was produced. Use of adhesive (FM-36) might improve this bond but would certainly not improve the basic composite structure. For this reason, efforts to produce a cylindrical model for test were discontinued.

CONCLUSIONS AND RECOMMENDATIONS

In the present work, Calspan has shown that the desired goal of at least a 10% reduction in weight of the M68 105mm gun tube can be attained using reinforced composite materials. In seeking solutions to attain this goal, we found that methods to reduce required working temperatures of the composite by possible increase of composite conduction would be fruitless because it is heat capacity per unit volume of the material rather than thermal conductivity that governs gun tube temperatures resulting from desired firing schedules. Computations of temperature levels as a function of axial station along the M68 tube with corresponding study of possible tube weight reductions at these stations suggests that efforts to reduce tube weight be directed chiefly to the breech section of the tube rearward of the bore evacuator. Here, the tube wall is thick and much weight

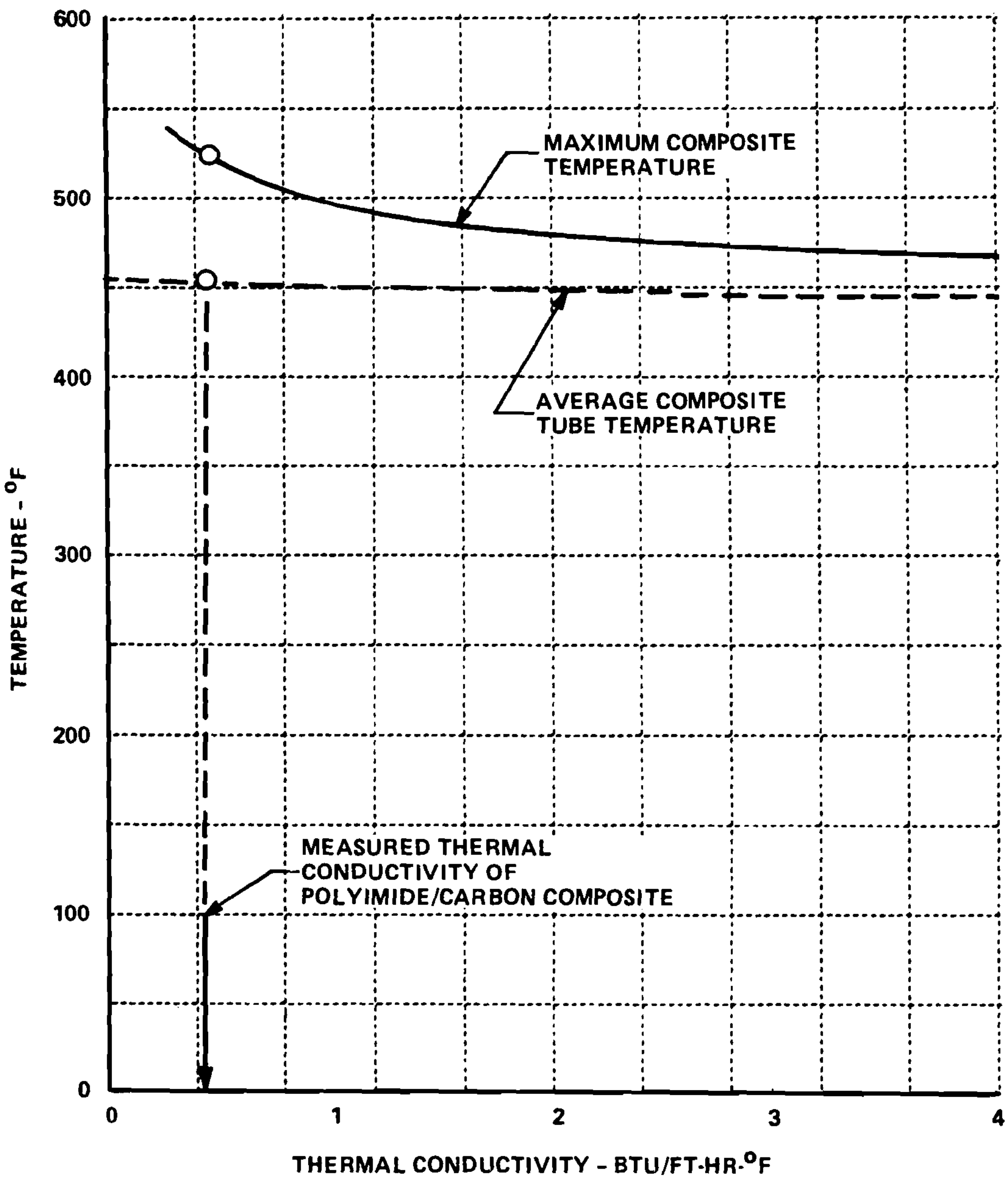

Figure 17. Effect of Composite Thermal Conductivity on Composite Temperatures at 63 Rounds

reduction can be achieved within the operating temperature range of existing polyimide/graphite composites.

A suggested composite tube which has been computed to withstand a full 65 round firing at 8 rounds/min is shown in Figure 18. Computed maximum composite temperatures for this configuration are as given in Figure 19. These are clearly below the 600°F working temperature for this composite.

Temperature/stress profiles for selected axial stations along the composite portion of the tube are detailed in the appendix. Table 11 summarizes the computed significant stresses in the composite tube section. A comparison with typical mechanical properties of both the composite and the steel indicates no expected failure during operation. Furthermore, combined stress profiles in the steel are very nearly the same as those for the monolithic steel tube, thus suggesting similar fatigue life.

A major obstacle to be overcome in the fabrication of any composite tube structured on a steel core is to provide an adequate bond between the steel and composite. For simplicity in fabrication, the bonding material should be able to be applied at the same time as the composite wrap and its curing temperature/process should be compatible with that of the composite resin. American Cyanamid's FM36 polyimide adhesive appears appropriate for use in the environment of interest and has been demonstrated to permit processing during cure of basic polyimide pre-preg fabric in sheet form. Whether similar compatibility can be achieved in large cylindrical layups should be the subject of future experimental effort.

With respect to other qualitative findings of this work, Calspan offers Table 12 which lists the important characteristics of a composite tube material and indicates the degree to which desired characteristics are presently met. Among those characteristics which may perhaps be major drawbacks against the fielding of a large caliber composite tube are:

- Ductility
- Impact strength
- Resistance-to-environment
- Fabricability
- Quality control/inspection
- Cost

We find that these particular characteristics are not in accord with those desired or required in a gun tube for battlefield use.

The low impact strength/ductility of typical composites could result in total loss of tube use under the action of small arms fire or shrapnel. Protection of the composite would negate weight savings, so it is not clear what means might be employed to accommodate this battlefield factor.

While the weathering resistance of the composite materials themselves may be adequate for use in field weapons, there is some question with regard to long-term effects of dirt, sun, moisture, salt spray, fungus, gun propellant residues, etc. on it or the bond between it and the metallic tube substrate.

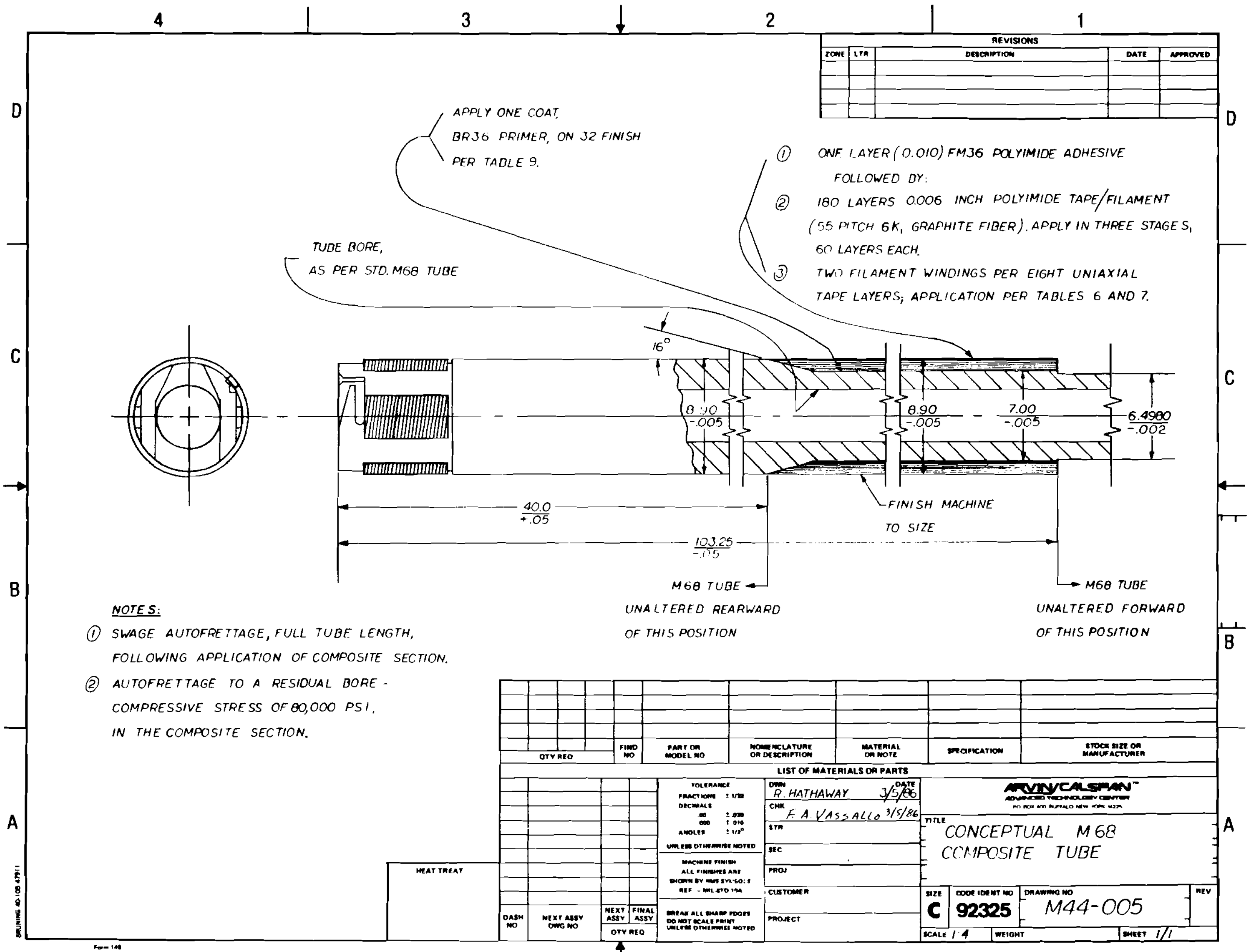

Figure 18. Suggested M68 Composite Tube Design

TABLE 11

Computed Composite Tube Stress Factors
for Suggested Design (Figure 14)
at 65 Rounds

Station from Breech inches	Combined Stresses in Steel Core psi Surface	Interface	Stresses in Composite - psi Hoop at Interface	Hoop at Outer Dia.	Maximum Combined Stress
45	86,507	85,928	14,323	10,966	15,351
60	86,470	79,866	11,429	8,750	13,195
75	86,537	75,990	10,016	7,668	13,470
103	86,713	69,843	7,957	6,092	14,332

NOTE: The initial cure stresses at all stations are:

Radial = 3,830 psi

Axial = -42,400 psi

Hoop = -16,300 psi

TABLE 12

Important Characteristics of a Composite Tube Material

Characteristic	Desired	Present Resin Composites
Tensile Strength	High	High
Stiffness	High	Moderate
Ductility	High	Low
Isotropy	High	Low
Thermal Expansion	Moderate	Low
Bond to Steel	High	Low (needs adhesive)
Impact Strength	High	Low
Thermal Stability	High	Low-to-Moderate
Volumetric Heat Capacity	High	Moderate
Density	Low	Low
Thermal Conductivity	Moderate	Low/High
Resistance to Environment	High	Low-to-Moderate
Fabricability	Simple	Complex
Machinability	Good	Good
Quality Control and Inspection	Well-defined	Undeveloped
Cost (raw material)	Low	Moderate-to-High

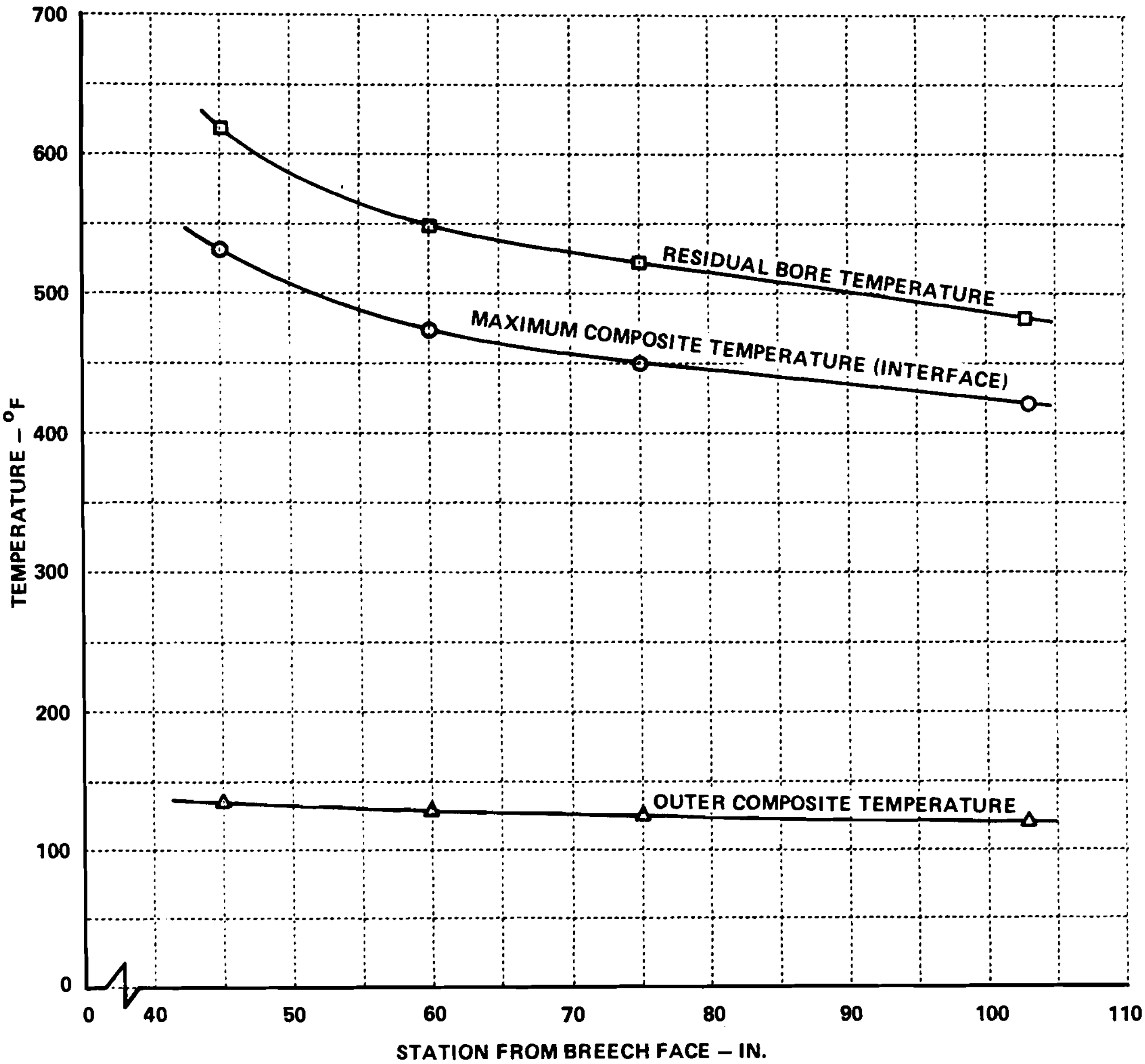

Figure 19. Computed Temperatures at 65 Rounds for Suggested Composite Tube Design (8 Rounds/Min)

Its performance under all possible environmental conditions must therefore be determined by controlled testing. This can be a rather costly proposition in itself.

There is little doubt, as discussed in the body of this report, that many problems of fabrication need solution if a reliable composite tube is to be fielded. Clearly, fabrication of the composite tube is of greater complexity than presently associated with the monolithic steel tube. When we consider that the entire process of tube autofrettage as applied to composite tube structures must be revisited through both analysis and fatigue testing, even greater complexity may be introduced.

Due to the very nature of the potential hazards associated with firing of high pressure cannons, present cannon tubes are manufactured under rather stringent specifications for materials properties, configuration, tolerances, and surface finish (both inner and outer). Procedures have been carefully developed for quality control and inspection of important facets of the tube design. Corresponding quality control and inspection procedures would need to be developed for composite tube structures. Non-homogeneity of the composite and possible localized inconsistencies in composite-to-metal bonding behavior, may make non-destructive testing procedures difficult to establish with sufficient degree of reliability.

The cost of manufacture of the composite tube will, in the short term, undoubtedly far exceed that of present monolithic steel tubes. Depending upon the tube stiffness requirements, the composite material cost alone could rival that of the completed monolithic tube. When we consider that 100 lb of composite must be utilized to attain a 10% tube weight savings and that high modulus fiber pre-pregs cost upwards of $200/lb, the cost of materials alone could be at least $20,000. Labor and/or facility costs are difficult to estimate at this juncture, but being expected to involve both engineering and highly experienced support personnel as well as unique facilities, these could be of similar magnitude. The basic steel substrate could perhaps be configured at about the same cost as that of the present tube. Thus, we estimate the composite tube to add approximately $40,000 to the cost of the present tube with no consideration given to costs of development of fabrication, quality control, new capital equipment, or testing procedures. Without such development, we would not recommend implementation of any composite tube design.

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APPENDIX A

Stress/Temperature Computer Code Listing

```
*....*...1.........2.........3.........4.........5.........6.........7.*.......8
C     THIS PROGRAM COMPUTES STRESS/TEMPERATURE PROFILES OF A COMPOSITE GUN TUBE
C      WALL DURING A FIRING SCHEDULE OF ONE OR MORE BURSTS AND COOLING PERIODS.
C
      DIMENSION TITLE(2Ø),T(1ØØ),TX(1ØØ)
C
C     DIMENSION ALL GEOMETRIC AND STRESS ARRAYS.
C
C     ALL STRESS ARRAYS ARE 4-LETTER MNEMONICS BEGINNING WITH "S".
C     THE 2ND LETTER DENOTES STRESS TYPE (AUTOFRETTAGE,CURE,PRESSURE,THERMAL...)
C     THE 3RD LETTER DENOTES STRESS DIRECTION (RADIAL,TANGENTIAL,AXIAL,COMBINED)
C     THE 4TH LETTER DENOTES STRESS SECTOR ("A" FOR R1 TO R2,"B" FOR R2 TO R3)
C
      DIMENSION  RA(5Ø),SARA(5Ø),SCRA(5Ø),SPRA(5Ø),SSRA(5Ø),STTA(5Ø),
     +          RAY(5Ø),SATA(5Ø),SCTA(5Ø),SPTA(5Ø),SSTA(5Ø),SSCA(5Ø)
      DIMENSION  RB(5Ø),SARB(5Ø),SCRB(5Ø),SPRB(5Ø),SSRB(5Ø),STTB(5Ø),
     +          RBY(5Ø),SATB(5Ø),SCTB(5Ø),SPTB(5Ø),SSTB(5Ø),SSCB(5Ø)
      DIMENSION         SSAA(5Ø),SSAC(5Ø),SSRC(5Ø),SSTC(5Ø),SSCC(5Ø),
     +         STAB(5Ø),SSAB(5Ø),SSAD(5Ø),SSRD(5Ø),SSTD(5Ø),SSCD(5Ø)
C
      REAL KA,KB,MAS,MTB
C
      READ (5,3ØØ) NRUN
C
      DO 999  K=1,NRUN
C
      READ (5,1ØØ) TITLE
      WRITE (6,15Ø) TITLE
C
C     ALL INPUT VALUES ARE EXPRESSED IN ENGLISH UNITS (FEET,SECONDS,DEG.F,ETC.).
C
C     INPUT INITIAL PRESSURE (P1) AND TEMPERATURE (T1), AMBIENT TEMPERATURE (TA)
C           EFFECTIVE TEMPERATURE (TEF), HEAT (Q1) AND EMISSIVITY (EMS).
C
      READ (5,2ØØ) P1,T1,TA,TEF,Q1,EMS
C
      P1Y = P1*144.Ø
C
C     INPUT CHAMBER PRESSURE (PCH), TOTAL MASS OF TUBE (MTB) AND MASS OF TUBE
C           FROM REAR FACE OF TUBE "RFT" TO AXIAL STATION OF INTEREST (MAS).
C
      READ (5,2ØØ) PCH,MTB,MAS
C
      PCHY = PCH*144.Ø
C
C     INPUT RADII (R1,R2,R3) AND DESIRED SECTOR ELEMENT SIZES (RLA,RLB).
C
      READ (5,2ØØ) R1,R2,R3,RLA,RLB
C
      R1Y = R1*12.Ø
      R2Y = R2*12.Ø
```

```
*....*...1.........2.........3.........4.........5.........6.........7.*.......8
            R3Y = R3*12.Ø
      C
      C     COMPUTE NUMBER OF RADIAL ELEMENTS AND FINAL ELEMENT SIZE IN EACH SECTOR.
      C
            ELA = (R2-R1)/RLA
            NLA = INT(ELA)
            RLA = (R2-R1)/FLOAT(NLA)
            RLAY = RLA*12.Ø
      C
            ELB = (R3-R2)/RLB
            NLB = INT(ELB)
            RLB = (R3-R2)/FLOAT(NLB)
            RLBY = RLB*12.Ø
      C
      C     DEFINE THE RADIAL INTERFACE ELEMENTS USED AS "DO LOOP" INTEGER VARIABLES.
      C
            L2  = NLA + 1
            L2A = L2 + 1
            L2B = L2 + 2
            L3  = L2 + (NLB+1)
            L3B = L3 - 1
      C
      C     INPUT CONVECTION COEFFICIENTS "H2" AND "H3" AT RADII "R2" AND "R3".
      C
            READ (5,2ØØ) H2,H3
      C
      C     OUTPUT INITIAL CONDITIONS (TEMPERATURE, PRESSURE, HEAT TRANSFER, GEOMETRY)
      C
            WRITE (6,35Ø) TA,EMS,T1,Q1,TEF,MTB,PCHY,MAS,P1Y,R1Y,R2Y,H2,R3Y,H3
      C
      C     INPUT MATERIAL PROPERTIES FOR SECTORS "A" AND "B".
      C      EG.FOR SECTOR "A": EXPANSION COEFFICIENT (AA), SPECIFIC HEAT (CA),
      C                         DENSITY (DA), ELASTIC MODULUS (EA), THERMAL
      C                         CONDUCTIVITY (KA), POISSON'S RATIO (UA)
      C                         YIELD STRENGTH IN SIMPLE TENSION (YA)
      C
            READ (5,2ØØ) AA,CA,DA,EA,KA,UA,YA, EL
            READ (5,2ØØ) AB,CB,DB,EB,KB,UB,YB,TCB
      C
      C     COMPUTE HEAT CAPACITY (CD_) OF MATERIAL IN EACH SECTOR.
      C
            CDA = CA*DA
            CDB = CB*DB
            EAY = EA*144.Ø
            EBY = EB*144.Ø
            ELY = EL*144.Ø
            YAY = YA*144.Ø
            YBY = YB*144.Ø
      C
            WRITE (6,4ØØ) NLA,NLB,RLAY,RLBY,AA,AB,CA,CB,DA,DB,CDA,CDB,KA,KB,
           +              EAY,EBY,ELY,UA,UB,YAY,YBY,TCB
      C
      C     INPUT START TIME (X), TIME PER SHOT (XS), AND COOLING TIME (XC).
      C
            READ (5,2ØØ) X,XS,XC
      C
```

```
      *....*...1.........2.........3.........4.........5.........6.........7.*.......8
      C      COMPUTE TIME STEP.
      C
             X1 = (CDA*RLA**2)/(2.Ø*KA*(1.Ø+H2*RLA/KA))
             X2 = (CDB*RLB**2)/(2.Ø*KB*(1.Ø+H2*RLB/KB))
             IF (X2.LT.X1) X1=X2
             X2 = (CDB*RLB**2)/(2.Ø*KB*(1.Ø+H3*RLB/KB))
             IF (X2.LT.X1) X1=X2
             X2 = XS/1Ø.Ø
             IF (X2.LT.X1) X1=X2
             IX2 = INT(XS/X1+1.Ø)
             XL = XS/FLOAT(IX2)+Ø.ØØØØ1
      C
      C      INPUT SHOTS/BURST (NSB), BURSTS (NB), AND # OF SHOTS TO PRINTOUT (NSTP).
      C
             READ (5,3ØØ) NSB,NB,NSTP
             WRITE (6,45Ø) NB,XC,NSB,XS
      C
      C      INITIALIZE COUNTERS FOR BURSTS FIRED (IB), "COOLING ROUNDS"
      C       FIRED (IC), PRINTOUTS (IP), AND "TOTAL ROUNDS" FIRED (IX).
      C
             IB = 1
             IC = Ø
             IP = 1
             IX = 1
      C
      C      DEFINE GEOMETRIC AND STRENGTH COEFFICIENTS USED IN THE STRESS COMPUTATIONS
      C
             CA1 = R2**2-R1**2
             CA2 = R2**2/CA1
             CA3 = (R2**2*(1.Ø-UA)+R1**2*(1.Ø+UA))/(EA*CA1)
             CA4 = R2**3*(1.Ø-UA)+R1**2*R2*(1.Ø+UA)
      C
             CB1 = R3**2-R2**2
             CB2 = R2**2/CB1
             CB3 = (R2**2*(1.Ø-UB)+R3**2*(1.Ø+UB))/(EB*CB1)
             CB4 = R2**3*(1.Ø-UB)+R3**2*R2*(1.Ø+UB)
             CB5 = CB4/(EB*CB1)
      C
             ARA = 3.1416*CA1
             ARB = 3.1416*CB1
      C
             CCA = EA/(1.Ø+(ARA*EA)/(ARB*EL))
             CCB = -CCA*ARA/ARB
      C
             CP1 = 2.Ø*R1**2*R2*(1.Ø-UB**2)
             CP2 = CB5*EA*CA1+CA4
             P2  = P1*CP1/CP2
      C
             CTA = AA*EA/(1.Ø-UA)
             CTB = AB*EB/(1.Ø-UB)
             CTL = AB*EL/(1.Ø-UB)
      C
             TAU = YA/2.Ø
             YSA = 1.1547*YA
      C
             CR1 = R1**2/(R3**2-R1**2)
```

```
      *....*...1.........2.........3.........4.........5.........6.........7.*.......8
            CR2 = (R2/R3)**2
            CR3 = (R2/R1)**2
            CR4 = (R3/R2)**2
      C
            PP2 = YSA/((((1.Ø-UB)*CR2+1.Ø+UB)/((EB/EA)*(1.Ø-CR2)))+1.Ø-UA)
            PP1 = PP2-YSA*ALOG(R1/R2)
            PE2 = PP1*2.Ø*R1**2*R2/((CB5*EA*CA1)+(R2**3*(1.Ø-UA)
           +                                   +R1**2*R2*(1.Ø+UA)))
      C
            WRITE (6,55Ø)
      C
            FAS = (1.Ø-MAS/MTB)*PCH*3.1416*R1**2
            FRA = FAS/(1.Ø+(ARB*EL)/(ARA*EA))
            FRB = FAS-FRA
      C
      C     COMPUTE AXIAL PRESSURE STRESSES IN SECTORS "A" (SPAA), AND "B" (SPAB).
      C
            SPAA = FRA/ARA*144.Ø
            SPAB = FRB/ARB*144.Ø
      C
      C     COMPUTE RESIDUAL (RADIAL/TANGENTIAL) AUTOFRETTAGE STRESSES AT RADIUS "R1".
      C
            SARA(1) = Ø.Ø
            SATA(1) = YSA-PP1+((PP1*(1.Ø+CR3)-2.Ø*PE2*CR3)/(1.Ø-CR3))
            IF (ABS(SATA(1)).LE.TAU)  FAC = 1.Ø
            IF (ABS(SATA(1)).GT.TAU)  FAC = TAU/ABS(SATA(1))
            SATA(1) = SATA(1)*144.Ø
            SATA(1) = SATA(1)*FAC
            WRITE (6,75Ø) R1Y,SARA(1),SATA(1),SPAA
      C
      C     SCALING COEFFICIENT "FAC" LIMITS THE RESIDUAL TANGENTIAL STRESS
      C                                AT THE BORE "R1"  TO -YA/2, OR "-TAU".
      C
      C     COMPUTE RESIDUAL (RADIAL/TANGENTIAL) AUTOFRETTAGE STRESSES IN SECTOR "A".
      C
            DO 1  J=2,L2
            RA(J) = R1+RLA*FLOAT(J-1)
            RAY(J) = RA(J)*12.Ø
            SARA(J) = YSA*ALOG(RA(J)/R2)-PP2+((PP1-PE2*CR3-(R2/RA(J))**2
           +                               *(PP1-PE2))/(1.Ø-CR3))
            SARA(J) = SARA(J)*144.Ø
            SARA(J) = SARA(J)*FAC
            SATA(J) = YSA*(1.Ø+ALOG(RA(J)/R2))-PP2+((PP1-PE2*CR3+(R2/RA(J))**2
           +                               *(PP1-PE2))/(1.Ø-CR3))
            SATA(J) = SATA(J)*144.Ø
            SATA(J) = SATA(J)*FAC
            WRITE (6,75Ø) RAY(J),SARA(J),SATA(J),SPAA
          1 CONTINUE
      C
      C     COMPUTE RESIDUAL (RADIAL/TANGENTIAL) AUTOFRETTAGE STRESSES AT RADIUS "R2".
      C
            SARB(L2A) = PE2-PP2
            SARB(L2A) = SARB(L2A)*144.Ø
            SARB(L2A) = SARB(L2A)*FAC
            SATB(L2A) = (PE2-PP2)*(1.Ø+CR4)/(1.Ø-CR4)
            SATB(L2A) = SATB(L2A)*144.Ø
```

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*....*...1.........2.........3.........4.........5.........6.........7.*.......8
      SATB(L2A) = SATB(L2A)*FAC
      WRITE (6,75Ø) R2Y,SARB(L2A),SATB(L2A),SPAB
C
C     COMPUTE RESIDUAL (RADIAL/TANGENTIAL) AUTOFRETTAGE STRESSES IN SECTOR "B".
C
      DO 2  J=L2B,L3
      RB(J) = R2+RLB*FLOAT(J-L2A)
      RBY(J) = RB(J)*12.Ø
      SARB(J) = (PE2-PP2)*(1.Ø-(R3/RB(J))**2)/(1.Ø-CR4)
      SARB(J) = SARB(J)*144.Ø
      SARB(J) = SARB(J)*FAC
      SATB(J) = (PE2-PP2)*(1.Ø+(R3/RB(J))**2)/(1.Ø-CR4)
      SATB(J) = SATB(J)*144.Ø
      SATB(J) = SATB(J)*FAC
      WRITE (6,75Ø) RBY(J),SARB(J),SATB(J),SPAB
    2 CONTINUE
C
C     INITIALIZE TEMPERATURE "T(I)" ARRAY AT INPUT TEMPERATURE "T1".
C
      DO 5  I=1,1ØØ
      T(I) = T1
    5 CONTINUE
C
C     COMPUTE MAXIMUM BORE TEMPERATURE (TB).
C
   1Ø TB = (1.Ø-T(1)/TEF)*(R1/(R1+Ø.25*RLA))/(CDA*RLA)*2.Ø*Q1
      T(1) = T(1)+TB
C
C     OUTPUT "MAXIMUM BORE TEMPERATURE" STATEMENT.
C
      WRITE (6,5ØØ) T(1)
C
      PR1 = P1
      PAB = P2
C
      SPZA = SPAA
      SPZB = SPAB
C
   15 X = X+XL
C
C     COMPUTE SURFACE TEMPERATURE AT RADIUS "R1".
C
      TX(1) = T(1)-((2.Ø*(R1+Ø.5*RLA)*KA*XL)/(CDA*(R1+Ø.25*RLA)*RLA**2))
     +          *(T(1)-T(2))
C
C     COMPUTE INTERNAL TEMPERATURES IN SECTOR "A".
C
      DO 2Ø J=2,NLA
      Z = ((KA*XL)/(CDA*RLA**2))/RA(J)
      W1 = (R1+Ø.5*(2.Ø*FLOAT(J)-3.Ø)*RLA)
      W2 = (R1+Ø.5*(2.Ø*FLOAT(J)-1.Ø)*RLA)
      TX(J) = Z*(W1*(T(J-1)-T(J))-W2*(T(J)-T(J+1)))+T(J)
   2Ø CONTINUE
C
C     COMPUTE TEMPERATURE AT INTERFACE OF SECTOR "A", AND RADIUS "R2".
C
```

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*....*...1.........2.........3.........4.........5.........6.........7.*.......8
      Z = (2.Ø*KA*XL)/(CDA*RLA**2.Ø*(R2-Ø.25*RLA))
      W1 = (R2-Ø.5*RLA)
      W2 = (H2*RLA*R2)/KA
      TX(L2) = Z*(W1*(T(NLA)-T(L2))-W2*(T(L2)-T(L2A)))+T(L2)
C
C     COMPUTE TEMPERATURE AT INTERFACE OF RADIUS "R2" AND SECTOR "B".
C
      Z = (2.Ø*KB*XL)/(CDB*RLB**2*(R2+Ø.25*RLB))
      W1 = H2*RLB*R2/KB
      W2 = R2+Ø.5*RLB
      TX(L2A) = Z*(W1*(T(L2)-T(L2A))-W2*(T(L2A)-T(L2B)))+T(L2A)
C
C     COMPUTE INTERNAL TEMPERATURES IN SECTOR "B".
C
      DO 25 J=L2B,L3B
      Z = (KB*XL)/(CDB*RLB**2*(R2+(FLOAT(J-L2A)*RLB)))
      W1 = (R2+Ø.5*(2.Ø*FLOAT(J-L2)-3.Ø)*RLB)
      W2 = (R2+Ø.5*(2.Ø*FLOAT(J-L2)-1.Ø)*RLB)
      TX(J) = Z*(W1*(T(J-1)-T(J))-W2*(T(J)-T(J+1)))+T(J)
   25 CONTINUE
C
C     COMPUTE OUTER BARREL TEMPERATURE AT RADIUS "R3".
C
      Z = (2.Ø*KB*XL)/(CDB*RLB**2*(R3-Ø.25*RLB))
      W1 = (R3-Ø.5*RLB)
      W2 = H3*RLB*R3/KB
      W3 = Ø.173*EMS*RLB*R3/(36ØØ.Ø*KB)
      G1 = W1*(T(L3-1)-T(L3))-W2*(T(L3)-TA)
      G2 = G1-Q3*(((T(L3)+46Ø.Ø)/1ØØ.Ø)**4-((TA+46Ø.Ø)/1ØØ.Ø)**4)
      TX(L3) = Z*G2+T(L3)
C
      DO 3Ø J=1,L3
      T(J) = TX(J)
   3Ø CONTINUE
C
C     IF THE SHOT HAS BEEN COMPLETED,  CONTINUE.   IF NOT,  GO BACK TO "15".
      IF (X.LT.FLOAT(IX)*XS) GO TO 15
C
C     COMPUTE AVERAGE TEMPERATURE FOR EACH SECTOR, AND FOR BOTH SECTORS.
C
      IZ = IX-IC
C
      TAA = ((R1+Ø.25*RLA)*RLA)*T(1)+((R2-Ø.25*RLA)*RLA)*T(L2)
C
      DO 4Ø J=2,NLA
      TAA = TAA+2.Ø*(R1+FLOAT(J-1)*RLA)*RLA*T(J)
   4Ø CONTINUE
C
      TAA = TAA/CA1
      TAB = ((R2+Ø.25*RLB)*RLB)*T(L2A)+((R3-Ø.25*RLB)*RLB)*T(L3)
C
      DO 45 J=L2B,L3B
      TAB = TAB+2.Ø*(R2+(FLOAT(J-L2)-1.Ø)*RLB)*RLB*T(J)
   45 CONTINUE
C
      TAB = TAB/CB1
```

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*....*...1.........2.........3.........4.........5.........6.........7.*.......8

C
      CDT = CDA*CA1+CDB*CB1
      TAT = (TAA*CDA*CA1+TAB*CDB*CB1)/CDT
C
      WRITE (6,6ØØ)
      WRITE (6,65Ø) IZ,X,T(1),TAA,T(L2A),TAB,T(L3),TAT
C
C     IF THE PRINT INTERVAL FOR THE TEMP ARRAY HAS BEEN COMPLETED,  GO TO "75".
      IF (IX.EQ.IP*NSTP) GO TO 75
C
C     IF THE COOLING PERIOD, FOLLOWING A BURST, HAS BEEN COMPLETED,  GO TO "95".
   55 IF (X.GT.FLOAT(IB)*((FLOAT(NSB)*XS)+XC)) GO TO 95
C
      IX = IX+1
C
C     IF THE BURST HAS BEEN COMPLETED,  CONTINUE.   IF NOT,  GO BACK TO "1Ø".
      IF (IX.LE.IB*NSB+IC) GO TO 1Ø
C
C     OUTPUT "IN COOLING PERIOD" STATEMENT.
C
      WRITE (6,7ØØ)
C
      IC = IC+1
C
      PR1 = Ø.Ø
      PAB = Ø.Ø
C
      SPZA = Ø.Ø
      SPZB = Ø.Ø
C
      GO TO 15
C
   75 DEL = AA*(TCB-TAA)-AB*(TCB-TAB)
C
      SCAA = DEL*CCA*144.Ø
      SCAB = DEL*CCB*144.Ø
C
      WRITE (6,8ØØ) SCAA,SCAB
      WRITE (6,85Ø)
C
C     COMPUTE AND OUTPUT ALL RADIAL & TANGENTIAL(HOOP) STRESSES AT RADIUS "R1".
C
      PR2 = (AA*(TAA-TCB)-AB*(TAB-TCB))/(CA3+CB3)
      CA5 = (R1**2*PR1-R2**2*PAB)/CA1
      CA6 = ((PR1-PAB)*R1**2*R2**2)/CA1
C
      SCRA(1) = Ø.Ø
      SCTA(1) = (-PR2)*CA2*2.Ø*144.Ø
      SPRA(1) = -PR1*144.Ø
      SPTA(1) = (CA5+CA6/R1**2)*144.Ø
      STTA(1) = (TAA-T(1))*CTA*144.Ø
      SSAA(1) = SCAA+SPZA+STTA(1)
      SSRA(1) = SPRA(1)
      SSTA(1) = SATA(1)+SCTA(1)+SPTA(1)+STTA(1)
      SSCA(1) = SQRT(((SSRA(1)-SSTA(1))**2+(SSTA(1)-SSAA(1))**2
     +                                     +(SSAA(1)-SSRA(1))**2)/2.Ø)
```

```
      *....*...1.........2.........3.........4.........5.........6.........7.*.......8
            SSAC(1) = SSAA(1)-SPZA
            SSTC(1) = SSTA(1)-SPTA(1)
            SSCC(1) = SQRT((SSTC(1)**2+(SSTC(1)-SSAC(1))**2+SSAC(1)**2)/2.Ø)
            WRITE (6,9ØØ) R1Y,T(1),SCRA(1),SPRA(1),
           +                       SCTA(1),SPTA(1),STTA(1),SSCA(1),SSCC(1)
      C
      C     COMPUTE AND OUTPUT ALL RADIAL & TANGENTIAL(HOOP) STRESSES IN SECTOR "A".
      C
            DO 8Ø J=2,L2
            SCRA(J) = (-PR2)*CA2*(1.Ø-R1**2/RA(J)**2)*144.Ø
            SCTA(J) = (-PR2)*CA2*(1.Ø+R1**2/RA(J)**2)*144.Ø
            SPRA(J) = (CA5-CA6/RA(J)**2)*144.Ø
            SPTA(J) = (CA5+CA6/RA(J)**2)*144.Ø
            STTA(J) = (TAA-T(J))*CTA*144.Ø
            SSAA(J) = SCAA+SPZA+STTA(J)
            SSRA(J) = SARA(J)+SCRA(J)+SPRA(J)
            SSTA(J) = SATA(J)+SCTA(J)+SPTA(J)+STTA(J)
            SSCA(J) = SQRT(((SSRA(J)-SSTA(J))**2+(SSTA(J)-SSAA(J))**2
           +                                  +(SSAA(J)-SSRA(J))**2)/2.Ø)
            SSAC(J) = SSAA(J)-SPZA
            SSRC(J) = SSRA(J)-SPRA(J)
            SSTC(J) = SSTA(J)-SPTA(J)
            SSCC(J) = SQRT(((SARA(J)-SSTC(J))**2+(SSTC(J)-SSAC(J))**2
           +                                  +(SSAC(J)-SARA(J))**2)/2.Ø)
            WRITE (6,9ØØ) RAY(J),T(J),SCRA(J),SPRA(J),
           +                          SCTA(J),SPTA(J),STTA(J),SSCA(J),SSCC(J)
         8Ø CONTINUE
      C
      C     COMPUTE AND OUTPUT ALL RADIAL & TANGENTIAL(HOOP) STRESSES AT RADIUS "R2".
      C
            SCRB(L2A) = -PR2*144.Ø
            SCTB(L2A) = PR2*CB2*(1.Ø+R3**2/R2**2)*144.Ø
            SPRB(L2A) = -PAB*144.Ø
            SPTB(L2A) = (PAB*(R2**2+R3**2)/CB1)*144.Ø
            STTB(L2A) = (TAB-T(L2A))*CTB*144.Ø
            STAB(L2A) = (TAB-T(L2A))*CTL*144.Ø
            SSAB(L2A) = SCAB+SPZB+STAB(L2A)
            SSRB(L2A) = SARB(L2A)+SCRB(L2A)+SPRB(L2A)
            SSTB(L2A) = SATB(L2A)+SCTB(L2A)+SPTB(L2A)+STTB(L2A)
            SSCB(L2A) = SQRT(((SSRB(L2A)-SSTB(L2A))**2+(SSTB(L2A)-
           +                 SSAB(L2A))**2+(SSAB(L2A)-SSRB(L2A))**2)/2.Ø)
            SSAD(L2A) = SSAB(L2A)-SPZB
            SSRD(L2A) = SSRB(L2A)-SPRB(L2A)
            SSTD(L2A) = SSTB(L2A)-SPTB(L2A)
            SSCD(L2A) = SQRT(((SSRD(L2A)-SSTD(L2A))**2+(SSTD(L2A)-
           +                 SSAD(L2A))**2+(SSAD(L2A)-SSRD(L2A))**2)/2.Ø)
            WRITE (6,9ØØ) R2Y,T(L2A),SCRB(L2A),SPRB(L2A),SCTB(L2A),
           +                         SPTB(L2A),STTB(L2A),SSCB(L2A),SSCD(L2A)
      C
      C     COMPUTE AND OUTPUT ALL RADIAL & TANGENTIAL(HOOP) STRESSES IN SECTOR "B".
      C
            DO 85 J=L2B,L3
            SCRB(J) = PR2*CB2*(1.Ø-R3**2/RB(J)**2)*144.Ø
            SCTB(J) = PR2*CB2*(1.Ø+R3**2/RB(J)**2)*144.Ø
            SPRB(J) = PAB*CB2*(1.Ø-R3**2/RB(J)**2)*144.Ø
            SPTB(J) = PAB*CB2*(1.Ø+R3**2/RB(J)**2)*144.Ø
```

```
      *....*...1.........2.........3.........4.........5.........6.........7.*.......8

            STTB(J) = (TAB-T(J))*CTB*144.Ø
            STAB(J) = (TAB-T(J))*CTL*144.Ø
            SSAB(J) = SCAB+SPZB+STAB(J)
            SSRB(J) = SARB(J)+SCRB(J)+SPRB(J)
            SSTB(J) = SATB(J)+SCTB(J)+SPTB(J)+STTB(J)
            SSCB(J) = SQRT(((SSRB(J)-SSTB(J))**2+(SSTB(J)-SSAB(J))**2
           +                                +(SSAB(J)-SSRB(J))**2)/2.Ø)
            SSAD(J) = SSAB(J)-SPZB
            SSRD(J) = SSRB(J)-SPRB(J)
            SSTD(J) = SSTB(J)-SPTB(J)
            SSCD(J) = SQRT(((SSRD(J)-SSTD(J))**2+(SSTD(J)-SSAD(J))**2
           +                                +(SSAD(J)-SSRD(J))**2)/2.Ø)
            WRITE (6,9ØØ) RBY(J),T(J),SCRB(J),SPRB(J),
           +                    SCTB(J),SPTB(J),STTB(J),SSCB(J),SSCD(J)
         85 CONTINUE
      C
            IP = IP+1
      C
            GO TO 55
      C
         95 IX = IX+1
            IB = IB+1
            IF (IB.GT.NB) GO TO 999
      C
            GO TO 1Ø
      C
        1ØØ FORMAT (2ØA4)
        15Ø FORMAT (1H1// ,T11,2ØA4/,T11,'-------------------------------------
           +------------------------------------------'////)
        2ØØ FORMAT (8F1Ø.5)
        3ØØ FORMAT (8I1Ø)
        35Ø FORMAT (  T4Ø,'INITIAL CONDITIONS:'///,T11,'AMBIENT TEMPERATURE (D
           +EG.F) = ',F6.1,4X,'EXT.TUBE SURFACE EMISSIVITY = ',F7.2//,T11,'INT
           +. GUN TUBE TEMP. (DEG.F) = ',F6.1,4X,'HEAT INPUT / SHOT (BTU/FT2)
           += ',F6.1//,T11,'EFFECTIVE GAS TEMP. (DEG.F) = ',F6.1//,T11,'OVERAL
           +L GUN TUBE MASS (LBM) = ',F6.1,4X,'MAX.CHAMBER PRESSURE (PSI) = ',
           +F7.1//,T11,'UPBORE(RFT) TUBE MASS (LBM) = ',F6.1,4X,   'MAXIMUM G
           +AS PRESSURE (PSI) = ',F7.1//,T11,'TUBE BORE RADIUS "R1" (IN.) = ',
           +F8.3//,T11,'INTERFACE RADIUS "R2" (IN.) = ',F8.3,2X,'CONVECTION CO
           +EFFICIENT "H2" = ',F7.2/,T54,'(BTU/SEC FT2 DEG.F)'/,T11,'EXT. TUBE
           + RADIUS "R3" (IN.) = ',F8.3,2X,'CONVECTION COEFFICIENT "H3" = ',F1
           +Ø.5//)
        4ØØ FORMAT (//,T21,'MATERIAL PROPERTIES:',T59,'SECTOR "A"',T79,'SECTOR
           + "B"'///,T11,'NO. OF FINITE ELEMENTS',T61,I2,T81,I2//,T11,'FINITE
           +ELEMENT SIZE (INCHES)',T56,F12.4,T76,F12.4//,T11,'THERMAL EXPANSIO
           +N COEFFICIENT (1/DEG.F)',T56,F14.6,T76,F14.6//,T11,'SPECIFIC HEAT
           +(BTU/LBM DEG.F)',T56,F13.5,T76,F13.5//,T11,'DENSITY (LBM/FT3)',T56
           +,F9.1,T76,F9.1//,T11,'HEAT CAPACITY (BTU/FT3 DEG.F)',T56,F1Ø.2,T76
           +,F1Ø.2//,T11,'THERMAL CONDUCTIVITY (BTU/SEC FT DEG.F)',T56,F13.5,T
           +76,F13.5//,T11,'MODULUS OF ELASTICITY (PSI)',T55,F1Ø.1,T75,F1Ø.1,
           +3X,'(HOOP)'/,T75,F1Ø.1,3X,'(AXIAL)'//
           +,T11,'POISSON"S RATIO',T56,F1Ø.2,T76,F1Ø.2//,T11,'YIELD STRENGTH (
           +PSI)',T56,F9.1,T76,F9.1//,T11,'CURE TEMPERATURE (DEG.F)',T76,F9.1/
           +/)
        45Ø FORMAT ( //,T11,'FIRING SCHEDULE:',3X,'TOTAL NO. OF BURSTS = ',I2,
           +3X,'TIME (SEC) BETWEEN BURSTS = ',F6.2//,T3Ø,'NO.OF SHOTS / BURST

           += ',I2,3X,'TIME (SEC) BETWEEN SHOTS =  ',F6.2/  ,1H1)
        5ØØ FORMAT (/,T19,'CURRENT MAXIMUM BORE TEMPERATURE (DEG.F) = ',F6.1/)
        55Ø FORMAT (/,T12,'RADIUS   AUTOFRETTAGE STRESSES (PSI)   AXIAL STRESS
           + (PSI)'/,T11,'(INCHES)      RADIAL     TANGENTIAL       (AT PEAK PRE
           +SSURE)')
        6ØØ FORMAT (     T11,'SHOT #  TIME(SEC)  TEMP."R1"  AVG."A"  TEMP."R2"
           + AVG."B"  TEMP."R3"  AVG."TUBE"'     )
        65Ø FORMAT (     T12,I3,T19,F7.2,6(4X,F6.1)    )
        7ØØ FORMAT (  /,T18,'"COMPOSITE GUN TUBE WALL IS COOLING"'/   )
        75Ø FORMAT (T12,F6.3,5X,F8.1,3X,F9.1,13X,F8.1)
        8ØØ FORMAT (/,T26,'AXIAL CURE STRESSES (PSI):  SECTOR"A"=',F8.1,' SECT
           +OR"B"=',F8.1 )
        85Ø FORMAT (/,T12,'RADIUS   TEMP.    RADIAL STRESSES (PSI)   TANGENTIA
           +L STRESSES (PSI)    COMBINED   -WITHOUT'/,T11,'(INCHES) (DEG.F)
           +  CURE    PRESSURE       CURE     PRESSURE    THERMAL      STRESS    PR
           +ESSURE')
        9ØØ FORMAT (T12,F6.3,3X,F5.1,2X,2(2X,F8.1),2X,3(2X,F8.1),2(3X,F8.1))
      C
        999 CONTINUE
            STOP
            END
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Typical Output Data

STRESS/TEMPERATURE PROFILES - 103 INCHES RFT - 105MM COMPOSITE GUN TUBE WALL

INITIAL CONDITIONS:

AMBIENT TEMPERATURE (DEG.F) =	70.0	EXT.TUBE SURFACE EMISSIVITY =	1.00
INT. GUN TUBE TEMP. (DEG.F) =	70.0	HEAT INPUT / SHOT (BTU/FT2) =	76.0
EFFECTIVE GAS TEMP. (DEG.F) =	2530.0		
OVERALL GUN TUBE MASS (LBM) =	1656.6	MAX.CHAMBER PRESSURE (PSI) =	60048.0
UPBORE(RFT) TUBE MASS (LBM) =	1281.0	MAXIMUM GAS PRESSURE (PSI) =	20995.2
TUBE BORE RADIUS "R1" (IN.) =	2.064		
INTERFACE RADIUS "R2" (IN.) =	3.324	CONVECTION COEFFICIENT "H2" = (BTU/SEC FT2 DEG.F)	1.20
EXT. TUBE RADIUS "R3" (IN.) =	3.504	CONVECTION COEFFICIENT "H3" =	0.00138

MATERIAL PROPERTIES:	SECTOR "A"	SECTOR "B"	
NO. OF FINITE ELEMENTS	6	2	
FINITE ELEMENT SIZE (INCHES)	0.2100	0.0900	
THERMAL EXPANSION COEFFICIENT (1/DEG.F)	0.000006	0.000006	
SPECIFIC HEAT (BTU/LBM DEG.F)	0.11735	0.11735	
DENSITY (LBM/FT3)	490.0	490.0	
HEAT CAPACITY (BTU/FT3 DEG.F)	57.50	57.50	
THERMAL CONDUCTIVITY (BTU/SEC FT DEG.F)	0.00555	0.00555	
MODULUS OF ELASTICITY (PSI)	29000016.0	29000016.0	(HOOP)
		29000016.0	(AXIAL)
POISSON"S RATIO	0.29	0.29	
YIELD STRENGTH (PSI)	159984.0	159984.0	
CURE TEMPERATURE (DEG.F)		350.0	

FIRING SCHEDULE:	TOTAL NO. OF BURSTS = 1	TIME (SEC) BETWEEN BURSTS = 150.00
	NO.OF SHOTS / BURST = 65	TIME (SEC) BETWEEN SHOTS = 15.00

RADIUS (INCHES)	AUTOFRETTAGE STRESSES (PSI) RADIAL	TANGENTIAL	AXIAL STRESS (PSI) (AT PEAK PRESSURE)
2.064	0.0	-79991.9	7233.8
2.274	-5895.8	-48796.1	7233.8
2.484	-8408.2	-23220.0	7233.8
2.694	-8702.5	-1734.7	7233.8
2.904	-7516.8	16679.0	7233.8
3.114	-5332.3	32724.9	7233.8
3.324	-2471.3	46904.1	7233.8
3.324	-2471.3	46905.0	7233.7
3.414	-1186.8	45620.5	7233.7
3.504	0.0	44433.7	7233.7

CURRENT MAXIMUM BORE TEMPERATURE (DEG.F) = 213.2

SHOT #	TIME(SEC)	TEMP."R1"	AVG."A"	TEMP."R2"	AVG."B"	TEMP."R3"	AVG."TUBE"
1	15.00	86.1	78.9	72.6	72.4	72.2	77.9

CURRENT MAXIMUM BORE TEMPERATURE (DEG.F) = 228.4

SHOT #	TIME(SEC)	TEMP."R1"	AVG."A"	TEMP."R2"	AVG."B"	TEMP."R3"	AVG."TUBE"
2	30.00	96.8	87.2	78.4	78.0	77.8	85.8

CURRENT MAXIMUM BORE TEMPERATURE (DEG.F) = 238.5

SHOT #	TIME(SEC)	TEMP."R1"	AVG."A"	TEMP."R2"	AVG."B"	TEMP."R3"	AVG."TUBE"
3	45.00	105.7	95.2	85.4	85.0	84.8	93.6

CURRENT MAXIMUM BORE TEMPERATURE (DEG.F) = 246.8

SHOT #	TIME(SEC)	TEMP."R1"	AVG."A"	TEMP."R2"	AVG."B"	TEMP."R3"	AVG."TUBE"
4	60.00	113.8	103.0	92.8	92.4	92.2	101.4

CURRENT MAXIMUM BORE TEMPERATURE (DEG.F) = 254.5

SHOT #	TIME(SEC)	TEMP."R1"	AVG."A"	TEMP."R2"	AVG."B"	TEMP."R3"	AVG."TUBE"
5	75.00	121.7	110.7	100.4	100.0	99.7	109.1

AXIAL CURE STRESSES (PSI): SECTOR"A"= -286.4 SECTOR"B"= 1581.8

RADIUS (INCHES)	TEMP. (DEG.F)	RADIAL STRESSES (PSI) CURE	PRESSURE	TANGENTIAL STRESSES (PSI) CURE	PRESSURE	THERMAL	COMBINED STRESS	-WITHOUT PRESSURE
2.064	121.7	0.0	-20995.2	-286.4	43645.3	-2682.0	37900.9	81516.6
2.274	120.2	-25.2	-15301.4	-261.1	37951.5	-2333.5	22956.6	47218.1
2.484	116.6	-44.3	-10989.6	-242.0	33639.7	-1430.3	26721.2	20659.4
2.694	111.7	-59.1	-7646.3	-227.2	30296.4	-251.0	38540.3	7469.7
2.904	107.0	-70.9	-5001.7	-215.5	27651.8	914.5	50594.9	21984.7
3.114	103.2	-80.3	-2873.9	-206.1	25524.0	1846.9	61443.1	36739.9
3.324	100.8	-88.0	-1136.5	-198.4	23786.6	2424.7	70986.6	49458.1
3.324	100.4	-88.0	-1136.5	1669.8	21570.6	-106.9	68381.1	49134.4
3.414	99.9	-42.2	-545.8	1624.1	20979.9	17.8	65361.7	47140.7
3.504	99.7	0.0	0.0	1581.8	20434.1	68.1	62550.8	45281.2

CURRENT MAXIMUM BORE TEMPERATURE (DEG.F) = 261.9

SHOT #	TIME(SEC)	TEMP."R1"	AVG."A"	TEMP."R2"	AVG."B"	TEMP."R3"	AVG."TUBE"
6	90.00	129.4	118.4	108.0	107.5	107.3	116.7

CURRENT MAXIMUM BORE TEMPERATURE (DEG.F) = 269.1

SHOT #	TIME(SEC)	TEMP."R1"	AVG."A"	TEMP."R2"	AVG."B"	TEMP."R3"	AVG."TUBE"

Final Shots and Cooling

CURRENT MAXIMUM BORE TEMPERATURE (DEG.F) = 601.6

SHOT #	TIME(SEC)	TEMP."R1"	AVG."A"	TEMP."R2"	AVG."B"	TEMP."R3"	AVG."TUBE"
63	945.06	487.5	476.4	464.4	463.4	462.5	474.4

CURRENT MAXIMUM BORE TEMPERATURE (DEG.F) = 606.4

SHOT #	TIME(SEC)	TEMP."R1"	AVG."A"	TEMP."R2"	AVG."B"	TEMP."R3"	AVG."TUBE"
64	960.06	492.6	481.5	469.5	468.5	467.6	479.5

CURRENT MAXIMUM BORE TEMPERATURE (DEG.F) = 611.2

SHOT #	TIME(SEC)	TEMP."R1"	AVG."A"	TEMP."R2"	AVG."B"	TEMP."R3"	AVG."TUBE"
65	975.06	497.6	486.5	474.5	473.5	472.6	484.5

AXIAL CURE STRESSES (PSI): SECTOR"A"= -347.6 SECTOR"B"= 1919.8

RADIUS	TEMP.	RADIAL STRESSES (PSI)		TANGENTIAL STRESSES (PSI)			COMBINED	-WITHOUT
(INCHES)	(DEG.F)	CURE	PRESSURE	CURE	PRESSURE	THERMAL	STRESS	PRESSURE
2.064	497.6	0.0	-20995.2	-347.6	43645.3	-2722.6	37891.7	81570.2
2.274	496.3	-30.6	-15301.4	-316.9	37951.5	-2390.8	22872.7	47265.9
2.484	492.7	-53.8	-10989.6	-293.8	33639.7	-1520.8	26585.3	20686.7
2.694	488.0	-71.8	-7646.3	-275.8	30296.4	-353.2	38418.9	7313.4
2.904	483.0	-86.0	-5001.7	-261.6	27651.8	861.9	50533.0	21913.7
3.114	478.6	-97.4	-2873.9	-250.1	25524.0	1935.1	61490.4	36773.9
3.324	475.3	-106.8	-1136.5	-240.8	23786.6	2760.3	71190.8	49633.4
3.324	474.5	-106.8	-1136.5	2026.6	21570.6	-253.4	68532.2	49271.2
3.414	473.4	-51.3	-545.8	1971.1	20979.9	11.4	65581.2	47335.9
3.504	472.6	0.0	0.0	1919.8	20434.1	222.1	62848.6	45542.4

"COMPOSITE GUN TUBE WALL IS COOLING"

SHOT #	TIME(SEC)	TEMP."R1"	AVG."A"	TEMP."R2"	AVG."B"	TEMP."R3"	AVG."TUBE"
65	990.05	489.3	484.2	477.4	476.5	475.7	483.0

"COMPOSITE GUN TUBE WALL IS COOLING"

SHOT #	TIME(SEC)	TEMP."R1"	AVG."A"	TEMP."R2"	AVG."B"	TEMP."R3"	AVG."TUBE"
65	1005.05	485.4	482.3	477.6	476.8	476.0	481.4

"COMPOSITE GUN TUBE WALL IS COOLING"

SHOT #	TIME(SEC)	TEMP."R1"	AVG."A"	TEMP."R2"	AVG."B"	TEMP."R3"	AVG."TUBE"
65	1020.04	483.0	480.6	476.7	475.9	475.2	479.9

"COMPOSITE GUN TUBE WALL IS COOLING"

SHOT #	TIME(SEC)	TEMP."R1"	AVG."A"	TEMP."R2"	AVG."B"	TEMP."R3"	AVG."TUBE"
65	1035.04	481.1	479.0	475.4	474.6	473.9	478.3

"COMPOSITE GUN TUBE WALL IS COOLING"

SHOT #	TIME(SEC)	TEMP."R1"	AVG."A"	TEMP."R2"	AVG."B"	TEMP."R3"	AVG."TUBE"
65	1050.04	479.5	477.5	473.9	473.2	472.5	476.8

AXIAL CURE STRESSES (PSI): SECTOR"A"= -113.2 SECTOR"B"= 625.3

RADIUS	TEMP.	RADIAL STRESSES (PSI)		TANGENTIAL STRESSES (PSI)			COMBINED	-WITHOUT
(INCHES)	(DEG.F)	CURE	PRESSURE	CURE	PRESSURE	THERMAL	STRESS	PRESSURE
2.064	479.5	0.0	0.0	-113.2	0.0	-492.4	80296.3	80296.3
2.274	479.3	-10.0	0.0	-103.2	0.0	-451.6	46347.0	46351.1
2.484	478.8	-17.5	0.0	-95.7	0.0	-336.0	20418.3	20421.4

APPENDIX B

Stress/Temperature Profiles for Suggested Composite Tube Design

(Figure 18)

STRESS/TEMPERATURE PROFILES - 45 INCHES RFT - 105MM COMPOSITE GUN TUBE WALL

INITIAL CONDITIONS:

AMBIENT TEMPERATURE (DEG.F) =	70.0	EXT.TUBE SURFACE EMISSIVITY =	1.00
INT. GUN TUBE TEMP. (DEG.F) =	70.0	HEAT INPUT / SHOT (BTU/FT2) =	101.0
EFFECTIVE GAS TEMP. (DEG.F) =	2900.0		
OVERALL GUN TUBE MASS (LBM) =	1492.0	MAX.CHAMBER PRESSURE (PSI) =	60000.0
UPBORE(RFT) TUBE MASS (LBM) =	600.0	MAXIMUM GAS PRESSURE (PSI) =	36388.0
TUBE BORE RADIUS "R1" (IN.) =	2.064		
INTERFACE RADIUS "R2" (IN.) =	3.504	CONVECTION COEFFICIENT "H2" = (BTU/SEC FT2 DEG.F)	0.70
EXT. TUBE RADIUS "R3" (IN.) =	4.450	CONVECTION COEFFICIENT "H3" =	0.00138

MATERIAL PROPERTIES:	SECTOR "A"	SECTOR "B"
NO. OF FINITE ELEMENTS	8	11
FINITE ELEMENT SIZE (INCHES)	0.1800	0.0860
THERMAL EXPANSION COEFFICIENT (1/DEG.F)	0.0000006	0.0000000
SPECIFIC HEAT (BTU/LBM DEG.F)	0.11735	0.31800
DENSITY (LBM/FT3)	490.0	110.0
HEAT CAPACITY (BTU/FT3 DEG.F)	57.50	34.98
THERMAL CONDUCTIVITY (BTU/SEC FT DEG.F)	0.00555	0.00015
MODULUS OF ELASTICITY (PSI)	28999984.0	6000000.0 (HOOP) 23499984.0 (AXIAL)
POISSON"S RATIO	0.29	0.35
YIELD STRENGTH (PSI)	159984.0	150048.0
CURE TEMPERATURE (DEG.F)		600.0

FIRING SCHEDULE:	TOTAL NO. OF BURSTS = 1	TIME (SEC) BETWEEN BURSTS = 150.00
	NO.OF SHOTS / BURST = 65	TIME (SEC) BETWEEN SHOTS = 7.50

RADIUS (INCHES)	AUTOFRETTAGE STRESSES (PSI) RADIAL	TANGENTIAL	AXIAL STRESS (PSI) (AT PEAK PRESSURE)
2.064	0.0	-79991.9	10828.4
2.244	-5376.8	-54844.2	10828.4
2.424	-8244.7	-33731.6	10828.4
2.604	-9366.9	-15672.2	10828.4
2.784	-9256.0	21.7	10828.4
2.964	-8264.4	13844.3	10828.4
3.144	-6639.6	26160.0	10828.4
3.324	-4558.4	37243.0	10828.4
3.504	-2148.6	47303.0	10828.4
3.504	-2148.6	9163.8	8774.7
3.590	-1881.0	8896.2	8774.7
3.676	-1631.9	8647.1	8774.7
3.762	-1399.7	8414.9	8774.7
3.848	-1182.9	8198.1	8774.7
3.934	-980.1	7995.3	8774.7
4.020	-790.2	7805.4	8774.7
4.106	-612.1	7627.3	8774.7
4.192	-444.9	7460.1	8774.7
4.278	-287.6	7302.8	8774.7
4.364	-139.6	7154.8	8774.7
4.450	0.0	7015.2	8774.7

CURRENT MAXIMUM BORE TEMPERATURE (DEG.F) = 793.7

SHOT #	TIME(SEC)	TEMP."R1"	AVG."A"	TEMP."R2"	AVG."B"	TEMP."R3"	AVG."TUBE"
65	487.61	619.0	572.4	533.8	256.3	135.3	457.6

AXIAL CURE STRESSES (PSI): SECTOR"A"= 2073.1 SECTOR"B"= -2210.1

RADIUS (INCHES)	TEMP. (DEG.F)	RADIAL STRESSES (PSI) CURE	PRESSURE	TANGENTIAL STRESSES (PSI) CURE	PRESSURE	THERMAL	COMBINED STRESS	-WITHOUT PRESSURE
2.064	619.0	0.0	-36388.0	610.6	70739.6	-11419.6	32899.9	86507.1
2.244	614.7	47.0	-28139.5	563.6	62491.2	-10355.6	33913.9	57861.3
2.424	603.5	83.9	-21659.4	526.6	56011.0	-7609.6	40972.2	34004.9
2.604	588.9	113.5	-16476.0	497.1	50827.7	-4032.6	50018.1	14986.8
2.784	574.1	137.5	-12265.1	473.1	46616.8	-404.3	58968.7	10227.4
2.964	561.0	157.3	-8797.9	453.3	43149.6	2805.6	67086.5	21973.8
3.144	550.3	173.7	-5909.0	436.9	40260.7	5420.2	74227.9	33878.4
3.324	542.1	187.6	-3476.5	423.0	37828.2	7424.1	80467.1	44324.7
3.504	536.3	199.4	-1409.2	411.2	35760.9	8854.4	85928.8	53393.8
3.504	533.8	199.4	-1409.2	-850.3	6010.1	0.0	15351.2	10395.6
3.590	456.2	174.5	-1233.6	-825.5	5834.6	0.0	14628.6	10038.4
3.676	389.4	151.4	-1070.3	-802.4	5671.2	0.0	13956.1	9710.6
3.762	332.7	129.9	-918.0	-780.8	5518.9	0.0	13329.5	9409.3
3.848	284.9	109.8	-775.8	-760.7	5376.7	0.0	12744.5	9132.2
3.934	245.3	90.9	-642.8	-741.9	5243.8	0.0	12197.7	8877.1
4.020	212.9	73.3	-518.3	-724.3	5119.2	0.0	11685.7	8641.9
4.106	187.1	56.8	-401.5	-707.7	5002.4	0.0	11205.7	8425.1
4.192	166.9	41.3	-291.8	-692.2	4892.7	0.0	10755.2	8224.9
4.278	151.9	26.7	-188.6	-677.6	4789.6	0.0	10331.7	8039.9
4.364	141.6	12.9	-91.5	-663.9	4692.5	0.0	9933.1	7868.9
4.450	135.3	0.0	0.0	-650.9	4601.0	0.0	9557.6	7710.7

"COMPOSITE GUN TUBE WALL IS COOLING"

SHOT #	TIME(SEC)	TEMP."R1"	AVG."A"	TEMP."R2"	AVG."B"	TEMP."R3"	AVG."TUBE"
65	495.11	599.3	570.0	539.6	260.3	137.7	457.5

STRESS/TEMPERATURE PROFILES - 60 INCHES RFT - 105MM COMPOSITE GUN TUBE WALL

INITIAL CONDITIONS:

AMBIENT TEMPERATURE (DEG.F) =	70.0	EXT.TUBE SURFACE EMISSIVITY =	1.00
INT. GUN TUBE TEMP. (DEG.F) =	70.0	HEAT INPUT / SHOT (BTU/FT2) =	87.0
EFFECTIVE GAS TEMP. (DEG.F) =	2775.0		
OVERALL GUN TUBE MASS (LBM) =	1492.0	MAX.CHAMBER PRESSURE (PSI) =	60000.0
UPBORE(RFT) TUBE MASS (LBM) =	800.0	MAXIMUM GAS PRESSURE (PSI) =	30988.0
TUBE BORE RADIUS "R1" (IN.) =	2.064		
INTERFACE RADIUS "R2" (IN.) =	3.504	CONVECTION COEFFICIENT "H2" = (BTU/SEC FT2 DEG.F)	0.70
EXT. TUBE RADIUS "R3" (IN.) =	4.450	CONVECTION COEFFICIENT "H3" =	0.00138

MATERIAL PROPERTIES:	SECTOR "A"	SECTOR "B"
NO. OF FINITE ELEMENTS	8	11
FINITE ELEMENT SIZE (INCHES)	0.1800	0.0860
THERMAL EXPANSION COEFFICIENT (1/DEG.F)	0.000006	0.000000
SPECIFIC HEAT (BTU/LBM DEG.F)	0.11735	0.31800
DENSITY (LBM/FT3)	490.0	110.0
HEAT CAPACITY (BTU/FT3 DEG.F)	57.50	34.98
THERMAL CONDUCTIVITY (BTU/SEC FT DEG.F)	0.00555	0.00015
MODULUS OF ELASTICITY (PSI)	28999984.0	6000000.0 (HOOP) 23499984.0 (AXIAL)
POISSON"S RATIO	0.29	0.35
YIELD STRENGTH (PSI)	159984.0	150048.0
CURE TEMPERATURE (DEG.F)		600.0

FIRING SCHEDULE:	TOTAL NO. OF BURSTS = 1	TIME (SEC) BETWEEN BURSTS = 150.00
	NO.OF SHOTS / BURST = 65	TIME (SEC) BETWEEN SHOTS = 7.50

RADIUS (INCHES)	AUTOFRETTAGE STRESSES (PSI) RADIAL	TANGENTIAL	AXIAL STRESS (PSI) (AT PEAK PRESSURE)
2.064	0.0	-79991.9	8400.5
2.244	-5376.8	-54844.2	8400.5
2.424	-8244.7	-33731.6	8400.5
2.604	-9366.9	-15672.2	8400.5
2.784	-9256.0	21.7	8400.5
2.964	-8264.4	13844.3	8400.5
3.144	-6639.6	26160.0	8400.5
3.324	-4558.4	37243.0	8400.5
3.504	-2148.6	47303.0	8400.5
3.504	-2148.6	9163.8	6807.3
3.590	-1881.0	8896.2	6807.3
3.676	-1631.9	8647.1	6807.3
3.762	-1399.7	8414.9	6807.3
3.848	-1182.9	8198.1	6807.3
3.934	-980.1	7995.3	6807.3
4.020	-790.2	7805.4	6807.3
4.106	-612.1	7627.3	6807.3
4.192	-444.9	7460.1	6807.3
4.278	-287.6	7302.8	6807.3
4.364	-139.6	7154.8	6807.3
4.450	0.0	7015.2	6807.3

CURRENT MAXIMUM BORE TEMPERATURE (DEG.F) = 701.7

SHOT #	TIME(SEC)	TEMP."R1"	AVG."A"	TEMP."R2"	AVG."B"	TEMP."R3"	AVG."TUBE"
65	487.61	548.3	507.4	473.6	231.9	126.6	407.3

AXIAL CURE STRESSES (PSI): SECTOR"A"= 6955.0 SECTOR"B"= -7414.6

RADIUS (INCHES)	TEMP. (DEG.F)	RADIAL STRESSES (PSI) CURE	PRESSURE	TANGENTIAL STRESSES (PSI) CURE	PRESSURE	THERMAL	COMBINED STRESS	-WITHOUT PRESSURE
2.064	548.3	0.0	-30988.0	2048.5	60241.9	-10018.1	34806.5	86470.7
2.244	544.5	157.7	-23963.6	1890.7	53217.5	-9084.2	30817.0	58352.5
2.424	534.7	281.6	-18445.1	1766.8	47699.0	-6673.9	35280.7	35434.7
2.604	521.9	380.7	-14031.0	1667.7	43284.9	-3534.8	43505.1	18297.5
2.784	508.9	461.3	-10445.0	1587.2	39698.9	-351.5	52295.8	13975.6
2.964	497.4	527.6	-7492.3	1520.9	36746.2	2463.4	60480.3	23067.9
3.144	488.0	582.8	-5032.1	1465.6	34286.0	4754.8	67774.2	33812.2
3.324	480.9	629.3	-2960.6	1419.1	32214.5	6509.1	74201.4	43607.2
3.504	475.8	668.9	-1200.0	1379.6	30453.9	7759.4	79866.1	52241.8
3.504	473.6	668.9	-1200.0	-2852.7	5118.2	0.0	13195.5	11923.0
3.590	405.9	585.5	-1050.6	-2769.4	4968.7	0.0	12662.0	11745.3
3.676	347.7	508.0	-911.4	-2691.8	4829.6	0.0	12169.2	11585.4
3.762	298.2	435.7	-781.8	-2619.5	4699.9	0.0	11713.3	11441.2
3.848	256.7	368.2	-660.7	-2552.0	4578.8	0.0	11291.2	11311.1
3.934	222.2	305.1	-547.4	-2488.9	4465.6	0.0	10899.8	11193.4
4.020	194.0	246.0	-441.4	-2429.8	4359.5	0.0	10536.7	11086.9
4.106	171.5	190.6	-341.9	-2374.4	4260.1	0.0	10199.3	10990.2
4.192	154.0	138.5	-248.5	-2322.3	4166.7	0.0	9885.6	10902.5
4.278	141.0	89.5	-160.6	-2273.4	4078.8	0.0	9593.7	10822.7
4.364	132.0	43.4	-77.9	-2227.3	3996.1	0.0	9321.9	10750.0
4.450	126.6	0.0	0.0	-2183.8	3918.2	0.0	9068.5	10683.7

"COMPOSITE GUN TUBE WALL IS COOLING"

SHOT #	TIME(SEC)	TEMP."R1"	AVG."A"	TEMP."R2"	AVG."B"	TEMP."R3"	AVG."TUBE"
65	495.11	531.0	505.4	478.8	235.3	128.7	407.2

STRESS/TEMPERATURE PROFILES - 75 INCHES RFT - 105MM COMPOSITE GUN TUBE WALL

INITIAL CONDITIONS:

AMBIENT TEMPERATURE (DEG.F) =	70.0	EXT.TUBE SURFACE EMISSIVITY =	1.00
INT. GUN TUBE TEMP. (DEG.F) =	70.0	HEAT INPUT / SHOT (BTU/FT2) =	82.0
EFFECTIVE GAS TEMP. (DEG.F) =	2680.0		
OVERALL GUN TUBE MASS (LBM) =	1492.0	MAX.CHAMBER PRESSURE (PSI) =	60000.0
UPBORE(RFT) TUBE MASS (LBM) =	980.0	MAXIMUM GAS PRESSURE (PSI) =	27000.0
TUBE BORE RADIUS "R1" (IN.) =	2.064		
INTERFACE RADIUS "R2" (IN.) =	3.504	CONVECTION COEFFICIENT "H2" = (BTU/SEC FT2 DEG.F)	0.70
EXT. TUBE RADIUS "R3" (IN.) =	4.450	CONVECTION COEFFICIENT "H3" =	0.00138

MATERIAL PROPERTIES:	SECTOR "A"	SECTOR "B"
NO. OF FINITE ELEMENTS	8	11
FINITE ELEMENT SIZE (INCHES)	0.1800	0.0860
THERMAL EXPANSION COEFFICIENT (1/DEG.F)	0.0000006	0.0000000
SPECIFIC HEAT (BTU/LBM DEG.F)	0.11735	0.31800
DENSITY (LBM/FT3)	490.0	110.0
HEAT CAPACITY (BTU/FT3 DEG.F)	57.50	34.98
THERMAL CONDUCTIVITY (BTU/SEC FT DEG.F)	0.00555	0.00015
MODULUS OF ELASTICITY (PSI)	28999984.0	6000000.0 (HOOP) 23499984.0 (AXIAL)
POISSON"S RATIO	0.29	0.35
YIELD STRENGTH (PSI)	159984.0	150048.0
CURE TEMPERATURE (DEG.F)		600.0

FIRING SCHEDULE: TOTAL NO. OF BURSTS = 1 TIME (SEC) BETWEEN BURSTS = 150.00

NO.OF SHOTS / BURST = 65 TIME (SEC) BETWEEN SHOTS = 7.50

RADIUS (INCHES)	AUTOFRETTAGE STRESSES (PSI) RADIAL	TANGENTIAL	AXIAL STRESS (PSI) (AT PEAK PRESSURE)
2.064	0.0	-79991.9	6215.4
2.244	-5376.8	-54844.2	6215.4
2.424	-8244.7	-33731.6	6215.4
2.604	-9366.9	-15672.2	6215.4
2.784	-9256.0	21.7	6215.4
2.964	-8264.4	13844.3	6215.4
3.144	-6639.6	26160.0	6215.4
3.324	-4558.4	37243.0	6215.4
3.504	-2148.6	47303.0	6215.4
3.504	-2148.6	9163.8	5036.6
3.590	-1881.0	8896.2	5036.6
3.676	-1631.9	8647.1	5036.6
3.762	-1399.7	8414.9	5036.6
3.848	-1182.9	8198.1	5036.6
3.934	-980.1	7995.3	5036.6
4.020	-790.2	7805.4	5036.6
4.106	-612.1	7627.3	5036.6
4.192	-444.9	7460.1	5036.6
4.278	-287.6	7302.8	5036.6
4.364	-139.6	7154.8	5036.6
4.450	0.0	7015.2	5036.6

CURRENT MAXIMUM BORE TEMPERATURE (DEG.F) = 666.8

SHOT #	TIME(SEC)	TEMP."R1"	AVG."A"	TEMP."R2"	AVG."B"	TEMP."R3"	AVG."TUBE"
65	487.61	521.6	483.0	451.0	222.7	123.4	388.4

AXIAL CURE STRESSES (PSI): SECTOR"A"= 8792.7 SECTOR"B"= -9373.8

RADIUS (INCHES)	TEMP. (DEG.F)	RADIAL STRESSES (PSI) CURE	PRESSURE	TANGENTIAL STRESSES (PSI) CURE	PRESSURE	THERMAL	COMBINED STRESS	-WITHOUT PRESSURE
2.064	521.6	0.0	-27000.0	2589.7	52489.1	-9473.6	36788.3	86537.2
2.244	518.0	199.4	-20879.6	2390.3	46368.6	-8590.3	28540.2	58656.3
2.424	508.7	356.0	-16071.3	2233.7	41560.4	-6310.8	30486.8	36141.6
2.604	496.6	481.4	-12225.3	2108.4	37714.3	-3342.0	38178.1	19700.4
2.784	484.3	583.1	-9100.8	2006.6	34589.8	-331.7	47130.0	15485.6
2.964	473.5	667.0	-6528.1	1922.7	32017.1	2330.0	55637.0	23658.2
3.144	464.6	736.8	-4384.5	1852.9	29873.5	4496.3	63273.3	33905.7
3.324	457.9	795.6	-2579.6	1794.1	28068.6	6154.6	70025.9	43418.1
3.504	453.1	845.6	-1045.6	1744.1	26534.7	7336.0	75990.9	51867.3
3.504	451.0	845.6	-1045.6	-3606.4	4459.5	0.0	13470.3	12944.9
3.590	387.0	740.3	-915.4	-3501.1	4329.3	0.0	13071.1	12818.3
3.676	332.1	642.2	-794.1	-3403.1	4208.1	0.0	12706.4	12704.9
3.762	285.4	550.8	-681.1	-3311.7	4095.1	0.0	12373.0	12603.2
3.848	246.1	465.5	-575.6	-3226.4	3989.6	0.0	12067.8	12511.8
3.934	213.6	385.7	-477.0	-3146.6	3890.9	0.0	11788.2	12429.5
4.020	187.0	311.0	-384.6	-3071.8	3798.5	0.0	11531.7	12355.2
4.106	165.8	240.9	-297.9	-3001.7	3711.8	0.0	11296.4	12288.1
4.192	149.3	175.1	-216.5	-2935.9	3630.4	0.0	11080.1	12227.4
4.278	137.0	113.2	-140.0	-2874.0	3553.9	0.0	10881.2	12172.2
4.364	128.5	54.9	-67.9	-2815.8	3481.8	0.0	10698.2	12122.2
4.450	123.4	0.0	0.0	-2760.8	3413.9	0.0	10529.6	12076.7

"COMPOSITE GUN TUBE WALL IS COOLING"

SHOT #	TIME(SEC)	TEMP."R1"	AVG."A"	TEMP."R2"	AVG."B"	TEMP."R3"	AVG."TUBE"
65	495.11	505.3	481.0	455.9	226.0	125.3	388.3

STRESS/TEMPERATURE PROFILES - 103 INCHES RFT - 105MM COMPOSITE GUN TUBE WALL

INITIAL CONDITIONS:

AMBIENT TEMPERATURE (DEG.F) =	70.0	EXT.TUBE SURFACE EMISSIVITY =	1.00
INT. GUN TUBE TEMP. (DEG.F) =	70.0	HEAT INPUT / SHOT (BTU/FT2) =	75.0
EFFECTIVE GAS TEMP. (DEG.F) =	2530.0		
OVERALL GUN TUBE MASS (LBM) =	1492.0	MAX.CHAMBER PRESSURE (PSI) =	60000.0
UPBORE(RFT) TUBE MASS (LBM) =	1120.0	MAXIMUM GAS PRESSURE (PSI) =	20995.0
TUBE BORE RADIUS "R1" (IN.) =	2.064		
INTERFACE RADIUS "R2" (IN.) =	3.504	CONVECTION COEFFICIENT "H2" = (BTU/SEC FT2 DEG.F)	0.70
EXT. TUBE RADIUS "R3" (IN.) =	4.450	CONVECTION COEFFICIENT "H3" =	0.00138

MATERIAL PROPERTIES:	SECTOR "A"	SECTOR "B"
NO. OF FINITE ELEMENTS	8	11
FINITE ELEMENT SIZE (INCHES)	0.1800	0.0860
THERMAL EXPANSION COEFFICIENT (1/DEG.F)	0.000006	0.000000
SPECIFIC HEAT (BTU/LBM DEG.F)	0.11735	0.31800
DENSITY (LBM/FT3)	490.0	110.0
HEAT CAPACITY (BTU/FT3 DEG.F)	57.50	34.98
THERMAL CONDUCTIVITY (BTU/SEC FT DEG.F)	0.00555	0.00015
MODULUS OF ELASTICITY (PSI)	28999984.0	6000000.0 (HOOP) 23499984.0 (AXIAL)
POISSON'S RATIO	0.29	0.35
YIELD STRENGTH (PSI)	159984.0	150048.0
CURE TEMPERATURE (DEG.F)		600.0

FIRING SCHEDULE: TOTAL NO. OF BURSTS = 1 TIME (SEC) BETWEEN BURSTS = 150.00

NO.OF SHOTS / BURST = 65 TIME (SEC) BETWEEN SHOTS = 7.50

RADIUS (INCHES)	AUTOFRETTAGE STRESSES (PSI) RADIAL	TANGENTIAL	AXIAL STRESS (PSI) (AT PEAK PRESSURE)
2.064	0.0	-79991.9	4515.9
2.244	-5376.8	-54844.2	4515.9
2.424	-8244.7	-33731.6	4515.9
2.604	-9366.9	-15672.2	4515.9
2.784	-9256.0	21.7	4515.9
2.964	-8264.4	13844.3	4515.9
3.144	-6639.6	26160.0	4515.9
3.324	-4558.4	37243.0	4515.9
3.504	-2148.6	47303.0	4515.9
3.504	-2148.6	9163.8	3659.4
3.590	-1881.0	8896.2	3659.4
3.676	-1631.9	8647.1	3659.4
3.762	-1399.7	8414.9	3659.4
3.848	-1182.9	8198.1	3659.4
3.934	-980.1	7995.3	3659.4
4.020	-790.2	7805.4	3659.4
4.106	-612.1	7627.3	3659.4
4.192	-444.9	7460.1	3659.4
4.278	-287.6	7302.8	3659.4
4.364	-139.6	7154.8	3659.4
4.450	0.0	7015.2	3659.4

CURRENT MAXIMUM BORE TEMPERATURE (DEG.F) = 617.1

SHOT #	TIME(SEC)	TEMP."R1"	AVG."A"	TEMP."R2"	AVG."B"	TEMP."R3"	AVG."TUBE"
65	487.61	483.9	448.4	419.0	209.8	118.9	361.7

AXIAL CURE STRESSES (PSI): SECTOR"A"= 11394.4 SECTOR"B"=-12147.4

RADIUS (INCHES)	TEMP. (DEG.F)	RADIAL STRESSES (PSI) CURE	PRESSURE	TANGENTIAL STRESSES (PSI) CURE	PRESSURE	THERMAL	COMBINED STRESS	-WITHOUT PRESSURE
2.064	483.9	0.0	-20995.0	3356.0	40815.1	-8697.5	44861.7	86713.3
2.244	480.5	258.4	-16235.8	3097.6	36055.9	-7886.6	30550.2	59200.8
2.424	472.0	461.4	-12496.9	2894.6	32317.1	-5793.5	26335.8	37289.0
2.604	460.9	623.8	-9506.3	2732.2	29326.4	-3067.6	31332.8	21786.8
2.784	449.6	755.7	-7076.7	2600.3	26896.8	-303.9	39773.8	17676.2
2.964	439.6	864.3	-5076.2	2491.7	24896.3	2139.6	48435.7	24643.5
3.144	431.5	954.8	-3409.3	2401.2	23229.4	4127.8	56403.5	34151.0
3.324	425.3	1031.0	-2005.8	2325.0	21826.0	5649.5	63522.2	43232.1
3.504	420.9	1095.8	-813.1	2260.2	20633.2	6733.0	69843.9	51399.2
3.504	419.0	1095.8	-813.1	-4673.5	3467.7	0.0	14332.3	14673.5
3.590	360.3	959.3	-711.8	-4537.0	3366.4	0.0	14097.0	14600.8
3.676	310.0	832.3	-617.5	-4410.0	3272.2	0.0	13885.0	14536.0
3.762	267.2	713.8	-529.7	-4291.6	3184.3	0.0	13693.6	14478.1
3.848	231.2	603.3	-447.6	-4181.0	3102.3	0.0	13520.6	14426.2
3.934	201.4	499.8	-370.9	-4077.6	3025.5	0.0	13364.0	14379.7
4.020	177.1	403.0	-299.0	-3980.8	2953.7	0.0	13222.1	14337.8
4.106	157.6	312.2	-231.6	-3889.9	2886.3	0.0	13093.2	14300.1
4.192	142.5	226.9	-168.3	-3804.6	2823.0	0.0	12976.0	14266.1
4.278	131.3	146.7	-108.8	-3724.4	2763.5	0.0	12869.4	14235.3
4.364	123.5	71.2	-52.8	-3648.9	2707.5	0.0	12772.1	14207.4
4.450	118.9	0.0	0.0	-3577.7	2654.6	0.0	12683.4	14182.1

"COMPOSITE GUN TUBE WALL IS COOLING"

SHOT #	TIME(SEC)	TEMP."R1"	AVG."A"	TEMP."R2"	AVG."B"	TEMP."R3"	AVG."TUBE"
65	495.11	468.8	446.6	423.5	212.8	120.6	361.6

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